DOCUMENT RESUME

ED 295 588 IR 013 181

TITLE Telecommunications Policy Research Conference. Competition in the Local Loop Section. Papers.
INSTITUTION Telecommunications Policy Research Conference, Inc., Washington, DC.
PUB DATE Sep 87
NOTE 96p.; Papers presented at the Telecommunications Policy Research Conference (15th, Airlie, VA, September 27-30, 1987). For the conference program and additional papers, see IR 013 160-182.
PUB TYPE Reports - Research/Technical (143) -- Speeches/Conference Papers (150)

EDRS PRICE MF01/PC04 Plus Postage.
DESCRIPTORS Cost Effectiveness; Mathematical Models; *Networks; Public Policy; Research and Development; *Research Needs; Technological Advancement; *Telecommunications; *Telephone Communications Industry; *Videotex
IDENTIFIERS *Fiber Optics; *Pricing

ABSTRACT

Four papers consider competition, new technology and economics of local telephone companies in a deregulated environment: (1) "An Engineering and Policy Analysis of Fiber Introduction into the Residential Subscriber Loop" (Marvin Sirbu, Frank Ferrante, and David Reed); (2) "Competition in the Local Loop: Pricing Carrier Access" (Steve G. Parsons); (3) Default Capacity Tariffs: Smoothing the Transitional Regulatory Asymmetrics in the Telecommunications Marketplace" (Dennis Weisman) (abstract only); and (4) "The Economics of Bypass in a Simple Model of the Telephone Network" (Glenn A. Woroch). The first paper is supplemented by 14 figures and 46 references, and the fourth paper includes a stylized model and six references. (EW)

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TELECOMMUNICATIONS POLICY RESEARCH CONFERENCE

Competition in the Local Loop Section

Airlie, Virginia

September 27-30, 1987

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An Engineering and Policy Analysis of Fiber Introduction into the Residential Subscriber Loop

by

Marvin Sirbu
Frank Ferrante
David Reed

November, 1987

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Support for this research was provided in part by a grant to CMU from Bell of Pennsylvania.

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1. Introduction

The rapid development of fiber optic technology over the last 10 years has kindled the imagination of telecommunications researchers who have begun visualizing a wideband fiber optic network that reaches every household and provides the infrastructure for a vast range of new services. Trials of fiber optic networks delivering video as well as traditional voice and data services are underway in North America, Europe and Japan. [8, 35, 41, 26, 31] As the narrow band Integrated Services Digital Network (N-ISDN) moves from research to reality, Broadband ISDN (B-ISDN) has become the new holy grail.

For such a vision to be realized, numerous technical, economic, marketing and political barriers must be overcome. But the rewards for the telecommunications industry and its equipment manufacturers are dazzling. At an estimated $2000 per subscriber for wiring the nation with fiber optics, the capital costs alone exceed $200 *billion*.

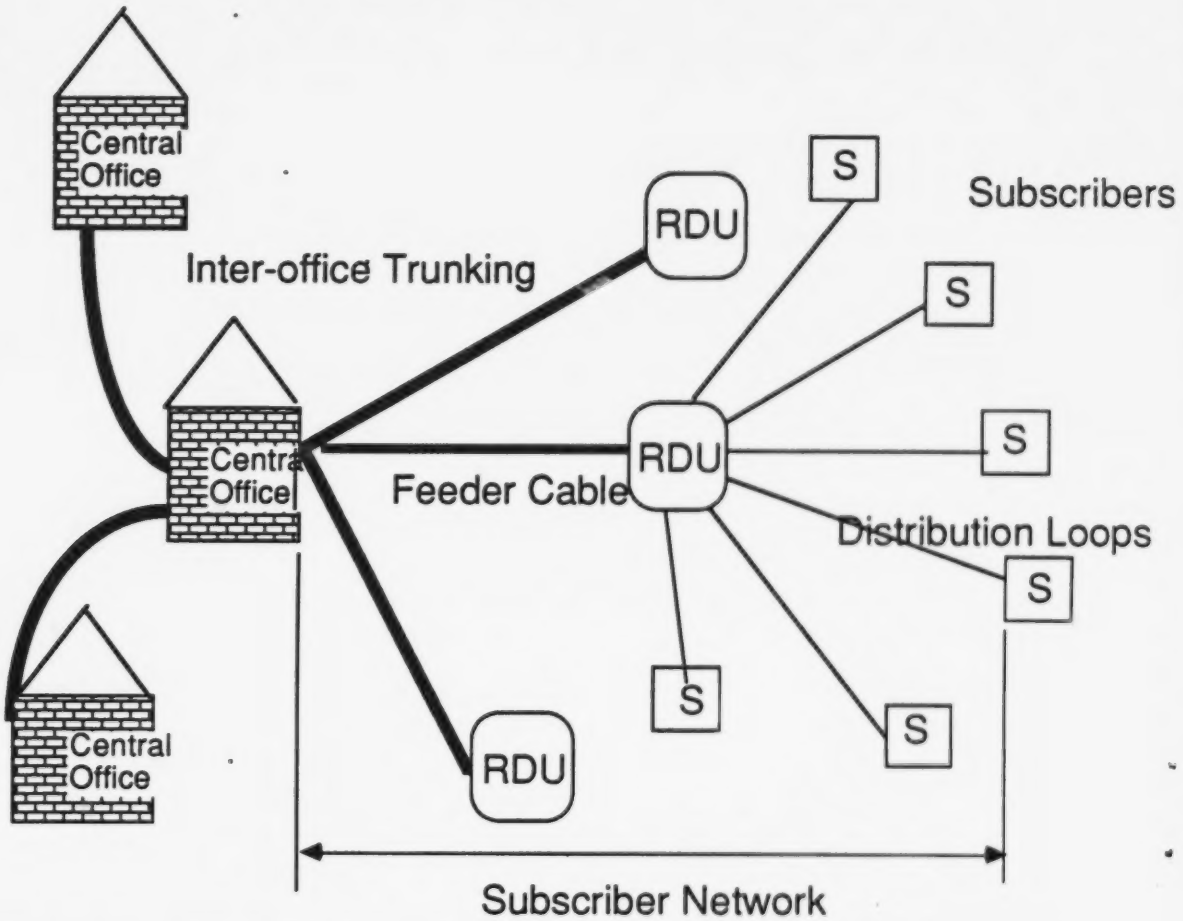
The successful implementation by the telephone industry of an infrastructure capable of readily delivering entertainment video, including video-on-demand, would create a powerful new competitor for CATV and over-the-air television, while creating entirely new options for "narrowcasting" or programming directed to small interest groups as opposed to a mass audience. The use of such a network for at last providing an acceptable "videophone" service could have profound sociological impacts.

In this paper, we present a preliminary analysis of the engineering, economic, and policy aspects of wiring the nation's residences with fiber optics. We focus on medium term (5 -10 year) technology options, and examine the economic implications of alternative architectures. Lastly, we consider several regulatory questions which are raised by our analysis.

1.1. Wideband Subscriber Networks

The development of fiber optic technology has been one of the most significant technological achievements of the past few decades. Today a single strand of glass fiber is used to carry digital signals at rates up to 1.7 Gbps -- the equivalent of more than 24,000 voice telephone calls or dozens of video channels, and the technology is still orders of magnitude below the theoretical limits. [37] Low attenuation reduces the need for repeaters to boost the signal over long distances. To date, fiber optics has been deployed primarily in the long distance network, where thousands of channels are needed between major switching centers. More recently, fiber has been used in local networks both for inter-office trunks and as feeder cable in the subscriber loop (Figure 1-1).

Figure 1-1: Telephone System Local Subscriber Loop Plant



By comparison, the ubiquitous copper wire telephone plant can carry signals of only a few megabits per second, and then only if costly-to-install repeaters are used every few thousand feet. It is not practical to use the existing copper plant for broadcast quality video. Current plans for narrowband ISDN stretch the

existing copper plant to its limits to provide a mere 144 Kbps, full duplex, to each subscriber.

The installation of a fiber optic connection from telephone switching offices to every subscriber would provide the capacity for an almost endless array of new services: entertainment video, including high definition television; high speed data services; and of course, traditional voice service.

The design of such a network requires hundreds of engineering tradeoffs to be analyzed, including:

- Should switching be concentrated in large central offices with relatively long fiber optic loops to the customer, or should switching be more distributed, thus allowing less fiber, at the price of more instances of switching electronics?
- Assuming that video signals are digitized, what bit rate should be used? Higher bit rates mean cheaper codecs, but lower bit rates mean more signals can be multiplexed onto a feeder cable. What is the cost effective capacity of a fiber?
- What is the design time horizon? Should the system be architected based on 1990's technology, or technology expected by the year 2000? How different would the system look under each set of assumptions? Can one architecture migrate gracefully to the other over time?

In addition to these engineering questions, a number of economic and marketing questions must be addressed:

- How much more expensive would a fiber optic network be than a copper network for new construction--even assuming that the fiber network includes only the bare minimum of capability needed to duplicate the copper network?
- What new service revenues would be required to justify retrofitting existing copper-served households with fiber? What services can be expected to generate these revenues?
- How long will it take to sign up subscribers for a new fiber optic network? How is the financial feasibility of a wideband network affected by assumptions about the time it takes to build up a sufficient subscriber base?
- How risky is an investment in a fiber optic network? Can capital spending be readily scaled to different rates of subscriber demand, or must the bulk of the investment be made up front?

A fiber optic subscriber network raises numerous policy questions as well:

- If entertainment video services are a key element in the financial success of a B-ISDN, how can the telephone companies deal with the limitations of the Cable Act of 1984, existing FCC cross-ownership restrictions, and the MFJ restrictions on information service offerings by the BOCs?
- What kind of franchise is needed from the authorities -- local, state and federal -- in order to install a new fiber optic local network?
- How can subscribers to existing copper-based services be protected from cross-subsidizing telephone company investments in fiber-based systems -- especially considering that the latter appears to fall under the classification of "basic" service, and thus will be lumped for accounting purposes with investments in copper-based plant?

1.2. Methodological Approach

In an attempt to shed some light on these questions, we have implemented an engineering/economic model of a residential subscriber fiber optic network. The model is similar to the many such models which have been reported on in part by vendors and carriers who are researching and promoting the B-ISDN concept. The key distinguishing feature of our model is that we are publishing it in its entirety.[1] By doing so, we hope to make it possible for a much larger number of concerned groups, whether regulators, consumers or telephone company competitors, to contribute in an informed way to the debate over the future of B-ISDN.

Our analysis has focused on the costs of a Fiber Optic Residential Subscriber Network (FORSN) from the telco central office out to the subscriber's premises. As suggested in Figure 1-1, these costs include equipment at the local central office, feeder cable, remote electronics (if any), distribution cable, and network termination equipment on customer premises. While a complete analysis would look at the entire area served by a central office and optimize the number and locations of various remote distribution units (RDUs), our model considers only a single RDU and spoke emanating from a central office.

2. Architectures for a Fiber Optic Residential Subscriber Network: Design Options

As suggested in the introduction, there are many tradeoffs that must be made in designing a fiber optic residential subscriber network. In this section, we review the principal architectures being discussed for a FORSN, and examine the component technologies whose cost and performance characteristics ultimately determine the feasibility of an overall architecture. These component or subsystem choices can in turn be grouped under the following headings: Fiber and electro-optics, channelization, and location of switching.

In analyzing alternative technologies and architectures it is important to be specific about the time horizon under consideration. Our analyses assume widespread introduction of an FORSN in the 1992-1997 timeframe. Consequently, in comparing technical options, we have made some allowance for the maturing of technologies which today are only available in prototype form. At the same time, some technologies, such as coherent modulation and detection have been judged sufficiently distant technologically, that we have not considered them in this analysis. [46] Similarly, we have assumed that widespread use of optical fiber for residential services will yield further reductions in cost below today's levels. Much as we have witnessed with N-ISDN, key circuit components will be implemented as single VLSI chips. Our technical and cost forecasts reflect these assumptions.

---

[1]The model has been implemented on the Demos Decision Modeling System developed at Carnegie Mellon University. Demos runs on a variety of Unix minicomputers and workstations including DEC VAX and Sun Microsystems. Please contact Marvin Sirbu for information on acquiring the model in machine readable form, and information on Demos licensing.

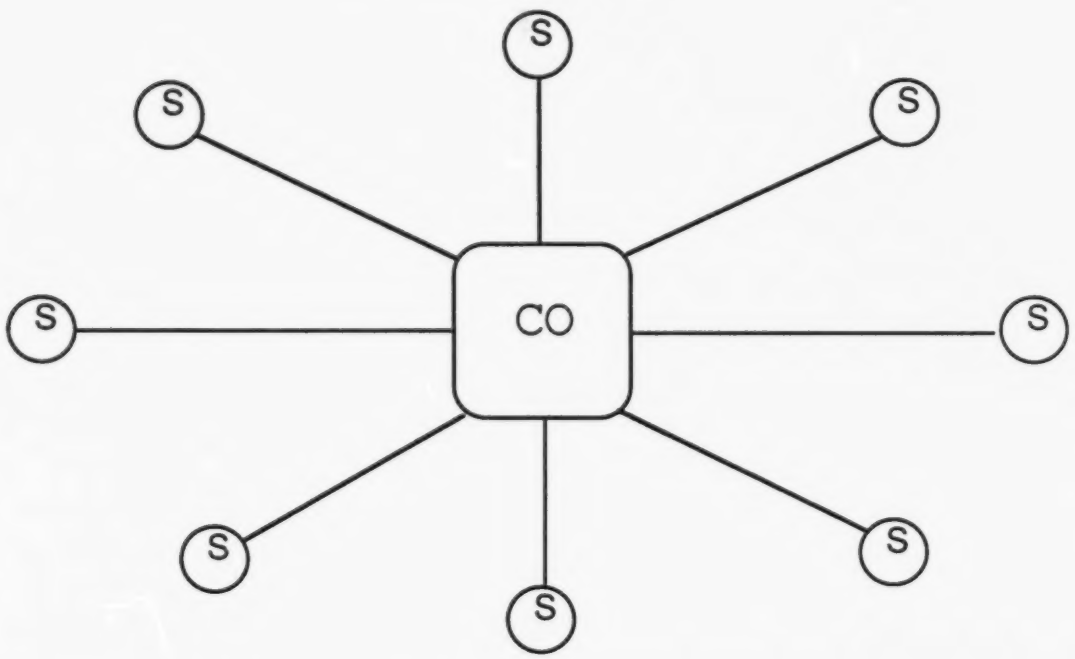
2.1. Alternative Architectures

The key decisions in any architecture revolve around where to put switching and multiplexing, and how to share transmission resources. The following examples illustrate the range of alternatives which have been presented in the literature.

2.1.1. Switched Star

At one extreme, researchers have proposed simple star networks, similar to the existing voice network. Individual fiber pairs would be laid from the central office to each subscriber, carrying signals for that subscriber only. All switching would be performed at the central office. In the limit, a separate fiber could be used for each video channel, in the event the subscriber has several televisions in use simultaneously tuned to different channels, much as multiple copper pairs are installed today when a subscriber has more than one telephone line.(Figure 2-1).

Figure 2-1: Switched Star



This design centralizes the switching electronics to take advantage of any economies of scale. The principal disadvantage is the amount of fiber required, since average loop lengths will be 4-5 kilometers, based on existing central office locations. This architecture makes the most sense when the cost of switching is high relative to the cost of transmission capacity.

2.1.2. Shared Fiber Bus

At the other extreme, a single fiber bus from the central office could carry television signals for dozens (--or, with coherent modulation techniques, thousands--) of signals to as many households by employing wavelength division or time division multiplexing. Optical splitters distributed along the bus would divert the signal to individual subscriber drops. Switching equipment on the subscriber premises would select out the subscriber's signal from among the many carried on the cable.

This architecture is similar to today's CATV systems. It is preferred when the cost of transmission is high relative to the cost of switching. While such a design economizes on fiber, it raises other problems. Tapping the bus frequently can lead to excessive signal losses, thus limiting the number of households that can be served. More expensive network termination equipment is needed to select the proper signal from the many carried on the cable. Adding subscribers without disrupting service to those farther down the line is a problem. Problems in securing information privacy are also raised by having the signals of several subscribers coming into each household.

2.1.3. Logical Star with Remote Multiplexing

As the previous example suggests, the amount of fiber required can be reduced dramatically by multiplexing several subscriber channels onto a high speed feeder fiber. In the logical star design, the feeders terminate in a remote multiplexing unit, and the individual subscriber's signal is carried the rest of the way on dedicated fiber. This configuration is similar to the ubiquitous digital loop carrier in today's copper telephone plant. Logically, such a network is a star, since each subscriber has a dedicated logical channel from his premises to the central office. Physically, however, it is a Double Star as shown in Figure 2-2.

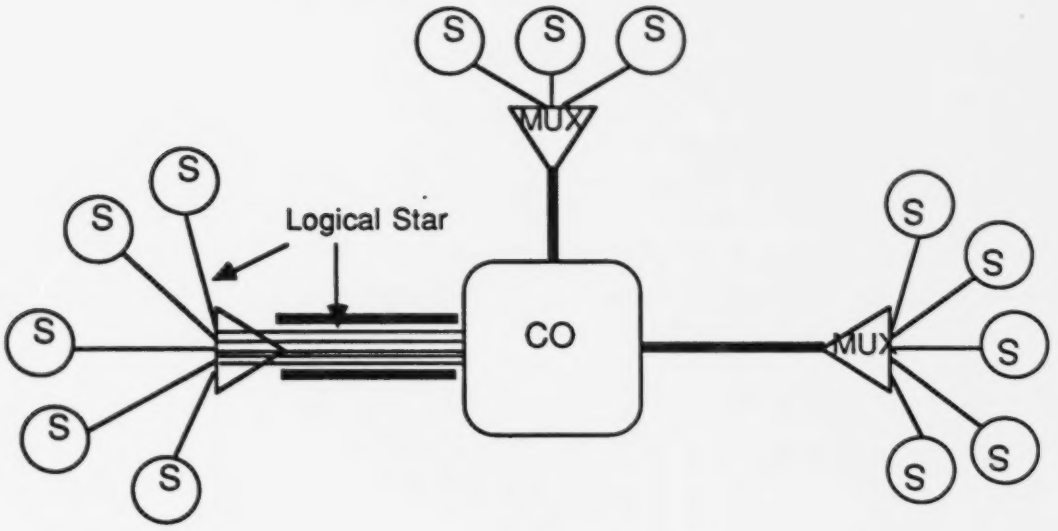
The logical star reduces the amount of fiber through multiplexing, with pair gain on the order of 12-30 depending upon bit rates in the feeder and distribution cables. Because the final distribution fiber carries signals for only a single household, there is no security issue as in the previous design. Additional subscribers can be added with no disruption of service as with bus systems.

Multiplexing can be by either wavelength division (WDM) or time division (TDM). If TDM is used more costly electro/optical interfaces and electronics are needed to handle higher speeds on the feeder cables, and for the multiplexors. If WDM is used, the multiple wavelengths must be filtered and sent to the appropriate distribution cable. The use of multiple wavelengths implies that subscriber equipment may not be standardized, but will vary according to the assigned wavelength. This can cause problems of inventory and maintenance. The alternative, a receiver capable of receiving any of a number of wavelengths is more costly.

2.1.4. Active Double Star

The amount of fiber in the feeder plant can be further reduced by deploying active switching units in the RDU. When multiple subscribers want to watch the same network TV broadcast simultaneously, a logical star must carry the same signal over the feeder cable many times. An active remote switching unit could

Figure 2-2: Logical Star with Remote Multiplexing



take one copy of the network broadcast from the feeder cable and replicate it onto the distribution fiber of many households. (See our discussion of the demand for video services in section 3.2.) Since upstream video traffic will be relatively infrequent -- at least until videophones take off --concentration by a remote switching unit can greatly reduce the number of feeder fibers dedicated to upstream traffic as well.

2.1.5. Passive Double Star

The light signal on a fiber can be split optically onto two or more fibers by simple passive devices. In a Passive Double Star, the signals for several households are multiplexed -- by either time division or wave division, or both -- onto a single fiber at the central office. At the RDU a passive splitter replicates the optical signal onto individual distribution fibers. Equipment at the subscriber's premise is directed to select the correct signal from the several multiplexed on the fiber. Configuring the network as a double star rather than as a bus simplifies maintenance by locating the passive splitter at a single well defined point. Also, there is less excess signal loss from a single 1:n splitter than from a succession of taps on a bus, thus allowing more subscribers to be served within the available signal power. However, the passive double star, like the Shared Fiber Bus, suffers from the same security problem and the need to have signal selection equipment on the subscriber's premises.

2.2. Component and Subsystem Issues

One cannot choose readily among these architectural alternatives without examining in more detail the choices available for the component technologies, and their economics. Thus, we turn now to a consideration of the subsystem choices which taken together determine the merits of particular architectures.

2.2.1. Fiber and Electro/Optics

Two types of fiber are in widespread use today: multimode and single mode. Multimode fiber, which typically has a core diameter of 62.5 microns is used primarily in local area networks and intra-building applications. It's large core diameter makes for easier splicing and allows better coupling with low-power sources such as inexpensive light emitting diodes (LEDs); it is also simpler to fabricate than single mode fiber. The principal drawback is that its information carrying capacity decreases sharply with distance by comparison with single mode fibers. Single mode fiber, with a 5 micron core, is the preferred choice for the interexchange network, where high channel capacity over long distances is desirable. Competition has led to the rapid introduction of single mode fiber (SMF) by U.S. Sprint, MCI and AT&T with the result that SMF costs have declined to be equal or even lower than multimode fiber. [33]

In the subscriber network, short loop length (90% of all subscriber loops in the U.S. are under 10 km.) and suggestions that subscribers may not need the larger capacity of single mode fiber have led some to propose the use of some multimode fiber for subscriber loop applications. [8, 21] Others have argued that installation now of single mode fiber, even if it is more costly at first, allows greater opportunity for future expansion of services not now anticipated. [6, 25].

In our analyses, we have assumed that single mode fiber will be the medium of choice throughout the subscriber loop plant. Based on a variety of sources, [45, 27, 15] we assume that SMF will be available at a price of $0.10/meter. Since this is a critical parameter we have examined alternative prices of 5 and 20 cents per meter. Current costs are in the vicinity of $.30/meter. [27]

In general, SMF with the lowest possible attenuation loss is more costly than fiber with higher attenuation. In the interexchange network, repeater costs can be reduced by deploying the lowest loss fiber; over the shorter distances found in the local loop, repeaters are typically unnecessary, and, it may not be worth the premium cost of extremely low loss fiber. [30] We assume attenuation and dispersion losses in the fiber amount to 1.0 dB/km.

Another cost trade-off issue involves the splicing and connecting of SMF. The cost of splicing and connectors increase with the accuracy of alignment. For example, misalignment of the fiber cores by 1μm to 3μm in a connector increases the losses from a few tenths of a dB to 2 dB, respectively, while decreasing the cost of the connector by a factor of three [2]. We assume losses of roughly 2 dB/connector and 1 dB/splice. The cost of installed connectors we have included explicitly at $30 each; splice costs vary depending upon whether single fibers or ribbon cable is being spliced.

Related to the choice of fiber is the issue of optical transmitters and receivers. Expensive laser diodes (LDs) are used throughout the inter-exchange fiber networks to achieve greater power input, allowing longer distances between repeaters. Light emitting diodes (LEDs) offer a less expensive and easier to manufacture alternative. [16] However, they are typically limited to bitrates of 200 Mbps and transmit considerably less power into the fiber. However, recent research suggests that edge-emitting LEDs can be used at bit rates as high as 560 Mbps over single mode fiber with adequate power coupling for local loop applications. [18] At the same time, widespread production of inexpensive LDs for use in consumer

compact disk players suggests that the cost of lasers for telecommunications applications could be sharply reduced in the future. Thus, the choice of LDs versus LEDs depends upon forecasts of future costs for each component type, as well as considerations of durability, power level required in a particular configuration, and the peak bit rate. [20]

Based upon the compact laser disc experience and private discussions [36] , we assume that the cost of a source operating at 600 Mbps or less will be $25, regardless of whether a LD or LED source is used. Laser diodes are used for feeder cables multiplexed to bitrates above 600 Mbps and the cost of a complete laser diode transmitter, suitable for mounting on a printed circuit board, including pigtail coupling, is assumed to cost $100. [16].

The alternative photodetectors available include the higher cost avalanche photodiodes (APDs) and the less expensive PIN photodiodes. Since the signal generated in the APD is internally amplified, the APD can detect lower optical power levels than the PIN photodiodes. PIN photodiodes are used for systems using low to moderate bitrates, while APDs are used for high bandwidth applications (typically greater than 1.5 G bps). [10] APDs are also more sensitive to temperature variations. The former we estimate to cost $100 each; [43] the PIN photodiodes $25.

The combination of optical sources and detectors to be used in a given configuration is determined by the optical power budget. In our analyses, we chose the cheapest combination of components which met the desired power margins. Edge-emitting LEDs are chosen over LDs, just as PIN photodiodes are chosen over APDs whenever the optical power levels made the exchange possible.

Finally, there is a choice between deploying two fibers to every subscriber -- one for each direction -- or to use a single fiber together with wavelength division multiplexing (WDM) -- a different frequency light source for signalling in each direction. Again, the tradeoff pits savings in fiber cost against the cost of the WDM equipment. [20, 1, 42] Our analysis suggests that it will be cheaper to use WDM on the distribution fibers, while designing for separate fibers in the feeder segments. The need to overbuild in the feeder plant in order to minimize the need for later reinforcement will generally provide sufficient extra fibers for the limited upstream traffic. Conversely, overbuilding in the distribution plant is far more costly, and thus should be minimized through the use of WDM. We have estimated the cost of wavelength division multiplexors/demultiplexors at $45 per port at each end.

2.2.2. Channelization

The wideband fiber into the home can carry a number of different services. How should these be multiplexed on the fiber, and what should be the standard data rates? The key tradeoff in setting these rates is between the capacity used, and the cost of signal processing and compression. For example, an NTSC video signal can be very cheaply digitized at 120 Mbps. [4] However, by investing in more costly encoding equipment, the signal can be reduced to 45 Mbps or even less. How important is it to save bandwidth at the price of more costly electronics? Should signal quality be reduced to simplify coding?

The tradeoff is rendered even more complex by the need to anticipate other services besides NTSC

video -- Extended Quality Television (EQTV), or High Definition Television (HDTV) are two examples. While the cost of transmitting an NTSC signal at 45 Mbps may be reasonable, compressing an HDTV signal to that rate would be extremely costly and perhaps technically infeasible. Users may also want access to high bit rate packet data services. Bellcore [6] has even suggested that voice traffic be packetized and sent over a high speed packet data channel.

A wide range of proposals have been suggested in the literature for the channelization of fiber to the home. [6, 22, 40, 3] We have chosen to consider two proposals in detail.

- The first option calls for a standard B-ISDN channel of around 150 Mbps, with the typical subscriber receiving up to four such channels for an aggregate data rate of 600 Mbps. [6, 25] A 150 Mbps channel can be used for an NTSC signal with no compression, while carrying HDTV with only modest compression. The four channels would be interleaved on a bit by bit basis according to the proposed SONET multiplexing scheme. [5] The choice of 150 Mbps as the basic video channel rate has gained support in recent CCITT discussions of standards for B-ISDN. [39]
- The second approach calls for video channels of roughly 44-45 Mbps (fitting inside current DS3 channels). The lower bit rate allows for more effective fiber pair gain when using passive splitters.

In both cases, we visualize an equivalent N-ISDN basic access rate or primary rate interface being multiplexed with the video channels. This allows the use of existing N-ISDN switching capacity, rather than replacing such capacity with, for example, wideband packet switches for both voice and data. Indeed, during the early trial deployment of fiber in old neighborhoods, voice may continue to be carried on existing copper pairs. Only in new construction should we expect to see all-fiber networks.

While considerations of electronics and transmitter/receiver costs limit total bit rate dedicated to a household to the 600 Mbps range, feeder cables may operate at considerably higher rates. Trials are currently underway in the long distance network of 1.7 - 2.24 Gbps equipment. [17] In the 1990s, we forecast a typical feeder rate of 2.4 Gbps, and consider rates as high as 5 Gbps.

2.2.3. Switching and Multiplexing

Switching video signals at 150 Mbps requires significantly different approaches than switching voice at 64 Kbps. Today's digital exchanges multiplex many voice conversations onto a high speed bus and then use time slot interchange to switch connections. Such an approach is prohibitively expensive for 150 Mbps channels. [40] The most widely proposed alternative is a space division switch with crosspoints implemented in a VLSI circuit. Several investigators [6, 40, 3, 12] have demonstrated prototype switching matrices capable of operating in the 150 Mbps range which is the peak rate envisioned for a video channel. Bellcore, for example has implemented a 16x16 cross point as a single integrated circuit of about 25 mm^2 in 2μ technology; and a 64x64 switch with all drivers, receivers and control logic has been built on a single card. [7] It appears, therefore, that relatively inexpensive switching for 150 Mbps digital video channels can be realized. In quantity, a CMOS chip of 25 mm^2 in 2μ technology can be produced for under $5 today. Thus, we believe that a 64x64 switching card will cost no more than $200, assembled and tested.

Multiplexing is the other key electronic technology. Several architectures call for multiplexing multiple video channels at rates up to 2.4 Gbps on feeder cables. These rates exceed the capabilities of CMOS technology, calling for gallium arsenide components of only medium scale integration. As a consequence, we believe such multiplexors will be considerably more costly than switching matrix components. We have estimated that such multiplexors will cost from $1200 - 2400 in large volume production.[2] It is for this reason that designs which call for TDM demultiplexors at the network termination point (e.g. passive star) are limited to bit rates far below the 2.4 Gbps capability of current optical fiber transmission systems.

A reasonable peak data rate for a CMOS/bipolar multiplexor is around 600 Mbps. Bussey has constructed such a multiplexor for combining up to four 150 Mbps channels to a subscriber in a single VLSI chip, plus an additional chip for framing and synchronizing the four channels. [6] Even where a subscriber receives only one video channel, such a multiplexor is needed for integrating a video channel with N-ISDN service channels. Based on these prototypes we have assumed that a subscriber line interface card containing multiplexors and framing, and LED optical transmitters for up to four subscribers can be fabricated on a single card at a cost of roughly $275.

3. Models and Assumptions

To analyze in more detail the tradeoffs associated with the design of a FORSN, we have constructed a simple engineering cost model for one quadrant of a network (Figure 1-1). The model assumes a central office providing N-ISDN and B-ISDN switching. We have looked at three alternative designs:

- Switched Star
- Active Double Star
- Passive Double Star

In the first model, fibers lead directly from a central office to the subscriber. In the other two models feeder fibers emanate from the CO and terminate in a Remote Distribution Unit which contains either active or passive equipment, according to the model. Distribution fibers provide the final link to the subscriber.

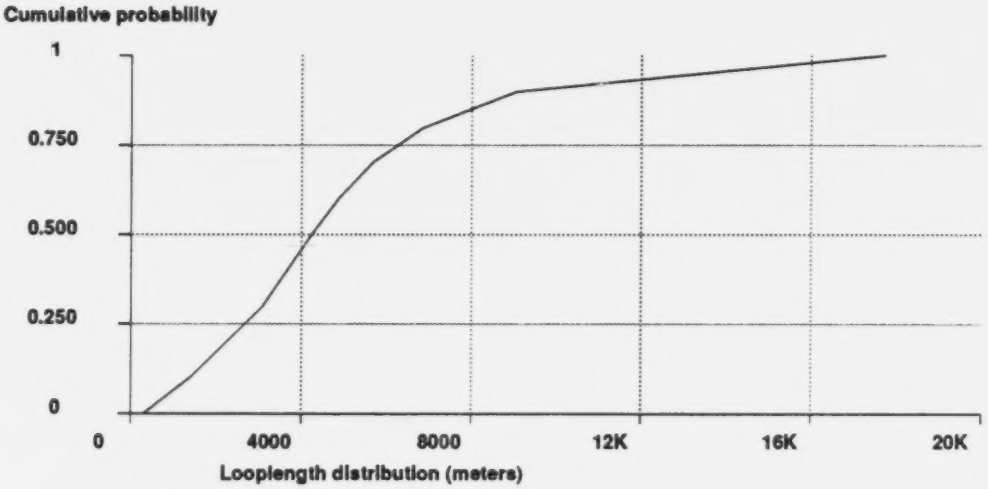
We have focused on the case where fiber is being overbuilt in a neighborhood already serviced by copper, since this will ultimately be the most common case. The RDU is assumed to service an area having a maximum of 1000 potential subscribers, although not all households are assumed to subscribe to fiber-based services. Those who do not subscribe have N-ISDN services provided over the existing copper plant, whose costs are assumed sunk. We also treat as sunk the costs of N-ISDN switching; switching costs at the CO include only the incremental costs to support video switching. Thus, the costs of fiber installation and related electronics must be born by only those subscribers who sign up for fiber-based services, of which the principal service is expected to be entertainment video. In particular, we

[2]The cost for such multiplexors also increases with the number of channels as a result of increased pin out, drivers, etc.

assume that enough distribution fiber is installed to handle every household should they eventually choose to subscribe. While this minimizes installation labor, it implies a substantial initial capital investment in fiber. Similarly, enough feeder fibers are installed initially to handle 100% penetration. Depending upon the rate at which subscribers sign up, it may be cheaper, in present value terms, to defer some fiber installation, even though going back to reinforce an existing installation has higher labor costs than installing it all at once. [9] We have not performed the dynamic analysis which would be necessary to shed light on this question.

The distance from the CO to the subscriber is based on data from two sources: Hightower provides a complete distribution of working loop lengths for the BellSouth region (Figure 3-1); [22] Singh provides mean working loop length, feeder length and distribution length based on the 1983 Bell System loop survey. [44] For our models we used the shape of the distribution from Hightower, but adjusted the mean feeder length using the data from Singh.

Figure 3-1: Cumulative Distribution Function for Working Length from CO to Subscriber for the BellSouth Region



The costs of installing fiber from an RDU to the subscriber can vary widely depending upon whether it is an urban neighborhood of high rise apartments or a suburban neighborhood with single family houses on two acre lots.

To obtain a representative value for the costs of the network between the RDU and the household, we assume the following:

- The serving area under consideration contains approximately 1000 households in a neighborhood laid out as a grid of six square blocks (and including both sides of the street on the outer perimeter); each block contains 24 living units.

- Lot size and average block length have been chosen to result in a typical density of 100 units per linear street mile (counting both sides).
- The RDU is positioned at the center of the serving area.

Normal planning rules for copper would call for large (e.g. 1200 pair) cables to be laid for one or two blocks from the RDU, and then spliced onto successively smaller cables branching out at intersections. The root and branch layout is typically done by hand based on standard design rules, such as the number of growth pairs to allow per household. We have performed a similar design for the fiber distribution cable in our models. However, because splicing costs are so much larger for fiber than for copper, we have chosen to run multiple smaller cables out from the RDU, terminating some on the nearby blocks and running others out to the perimeter. This eliminates the need for splicing, other than for the drop cable to the subscriber.

We also assume that the fiber optic cables will only be available in certain sizes. At present, there are no standard sizes for fiber optic cable for use in the distribution loop; we have thus selected standard sizes convenient for our models. For example, in the star and active double star architecture, we assume that a standard fiber cable contains 36 fibers. In the passive double star, cables are available only in multiples of 12 fibers. A protection factor specifies the percentage of dark fiber which is installed to cover either fiber failures or growth in the future. Inner duct is installed for each distribution cable.

Drop cables are spliced to the distribution cable and run from manholes (assumed to be spaced one or two per block) to the residence. Drop cables are installed without inner duct but with a rodent-proof sheath.

In all of our models customers are provided with downstream video services, and full duplex N-ISDN services. *We have not considered upstream video from the home, as would be required for videotelephony.* We have made this assumption in our effort to identify a fiber system capable of competing with CATV, but with the lowest possible entry cost.

The appendix provides the details of our models. The assumptions regarding electronics costs, demand, and cable costs are common to all of the models. The equations specific to each of the architectures analyzed are given in their respective listings.

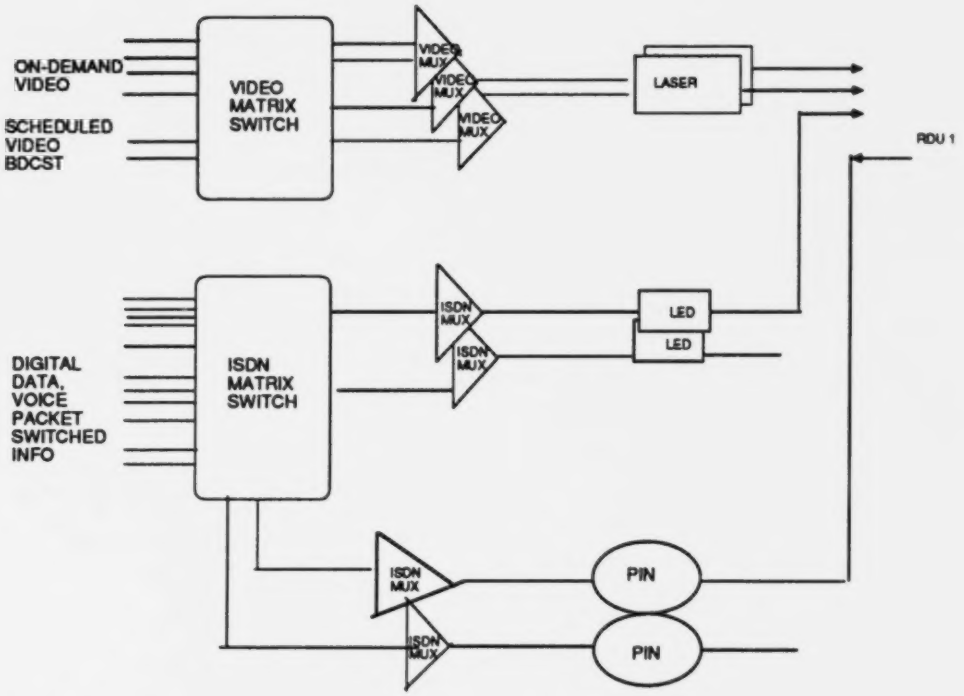
3.1. Active Double Star

We shall consider the Active Double Star model first, both because it illustrates most of the technologies we have examined, and because it has received a great deal of attention, particularly from Bellcore. [6, 25]

Video signals and N-ISDN signals arrive at a central office on incoming trunks. The standard data rate for a video signal is 150 Mbps; N-ISDN services are at the basic access rate of 144 Kbps. Separate switching matrices are assumed to be used for each signal (Figure 3-2). The outputs of each switching matrix are time division multiplexed onto feeder fibers from the central office to the RDU. Two fibers are

dedicated to carrying multiplexed N-ISDN traffic: one in each direction. As many fibers as are necessary to carry the estimated peak demand are devoted to downstream video traffic. Feeder fibers operate at 2.4 Gbps.

Figure 3-2: Central Office Configuration



At the RDU, the video signals are demultiplexed and fed to a remote switching unit based on CMOS cross-points operating at 150 Mbps. The N-ISDN signals are simply demultiplexed, with no remote switching assumed. Up to four video outputs are then multiplexed together with an N-ISDN basic rate interface for transmission on the distribution fibers to the subscriber (Figure 3-3). An upstream channel is needed for the N-ISDN traffic. Rather than supply two fibers to every household, we assume that a single fiber is used together with wavelength division multiplexors at the subscriber's premises and at the RDU.

At the subscriber's premises, the signals are demultiplexed, and the digital video signals are converted to analog for a standard TV (Figure 3-4).

Call set-up for both voice and video is assumed to be conveyed via the N-ISDN D channel to the central office. The CO then insures that the correct video signals are sent to the RDU and controls the video switch in the RDU to send the correct signal to the subscriber's line.

Figure 3-3: RDU for Active Double Star

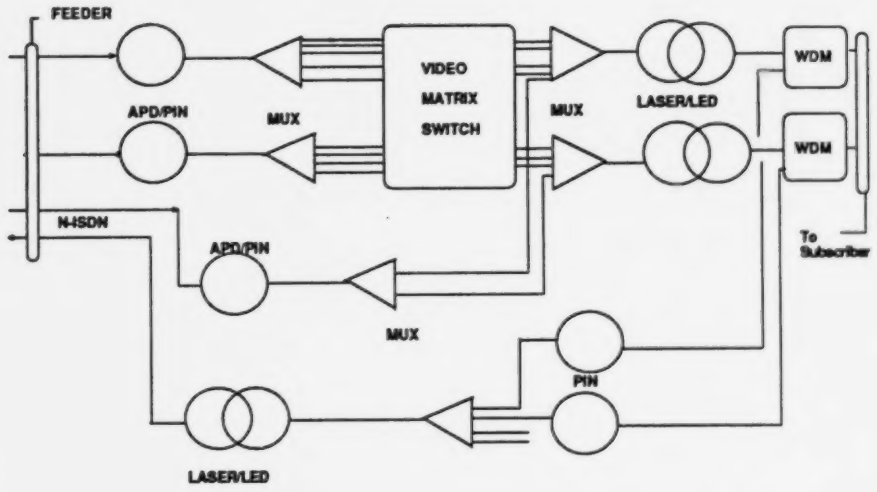
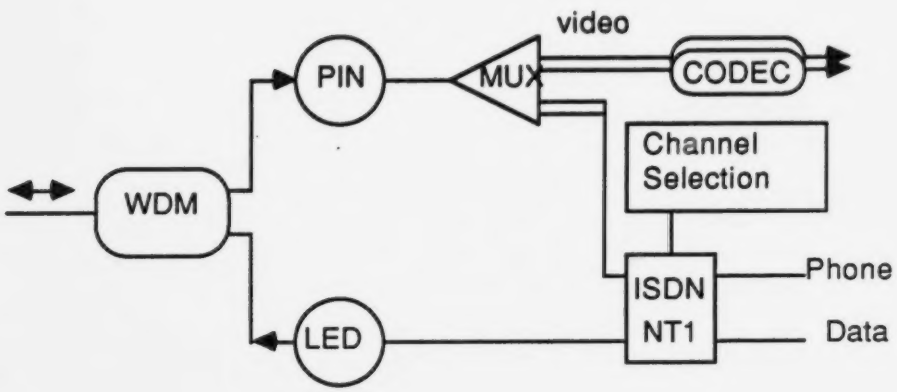


Figure 3-4: Subscriber's Premises Equipment



3.2. Demand for Video Services

While much has been written regarding future services to the home, [24] we believe the principal source of revenue to cover the cost of installing fiber will be the delivery of entertainment video. Indeed, many of the new services which have been described in the literature can be delivered perfectly well via N-ISDN over copper loops. Only moving images require the bandwidth of fiber.

Video services can be of two types: *Distributive* video, in which a common broadcast signal is delivered to many households simultaneously, and some form of *Video on Demand* in which the subscriber receives a unique signal meant only for him or her. An example of the latter would be a subscriber dialing into an automated videodisk "jukebox" to receive a particular movie.

Estimating the number of subscribers who at any one time will prefer to watch distributive video versus on-demand video is critical to sizing the feeder plant and the remote switching unit. For example, assume that during the peak hour some 500 subscribers served by an RDU are watching television. As many as 90% may be watching one of the four major networks or other continuously broadcast channel such as HBO or ESPN, while 10% are watching some unique program. In an active double star network, only 6 channels would be needed on the feeder fiber to carry the distributive video signals watched by 90% of the subscribers, while 50 additional channels will be needed to carry the on-demand video requested by the remaining 10%.

Our model assumes that 36 channels of distributive video are automatically provided to the RDU from the central office. Requests for distributive video programs beyond these 36 channels are handled the same as demand-video requests.

In order to estimate the actual number of channels required for demand-video, we have constructed a traffic model for on-demand video services. Such a model is characterized by:

- The arrival statistics of the on-demand video requests
- The probability distribution of holding times for on-demand video service
- The nature of the queue - in our case we assume that requestors who find no available channel abandon their request.

In order to apply classic queuing theory principles to this problem we must make some additional assumptions about the traffic statistics.

1. That the statistical parameters are stationary.
2. That the process satisfies the Markov criterion: the probability of changing state depends only on the current state, and not on the history of how one arrived at a state.

Clearly, we do not expect all the statistical parameters to be completely independent of time. Instead we expect on-demand video traffic to peak at certain times just as telephone traffic has observed peak periods of demand. However, we are assuming that for a given interval of time -- denoted as the busy period, *e.g.* from 7 - 10 p.m. on weekend evenings -- the relevant statistical parameters are essentially constant throughout the time interval and the system has reached equilibrium.

For simplicity in the analysis, we also make two more assumptions:

3. Video requests form a Poisson process
4. The number of subscribers potentially making video requests is large enough so that the probability of a request in any time interval does not depend upon the number of prior requestors already being served.

The latter requirement insures that the arrival statistics don't change simply because the available pool of requestors has been depleted by the number of people already being served. The number 200 is often cited as the point at which the pool of subscribers is large enough to satisfy this criterion. [14] Since the number of subscribers served by one RDU is in the range of 200 - 1000, this condition is likely to be satisfied.

We have assumed a Poisson arrival process which means that the probability of n requests arriving over a time interval T is given by:

$$g(n) = \frac{(\lambda T)^n}{n!} e^{-\lambda T}$$

where the average number of incoming requests over time T is λT. The average on-demand video traffic (measured in erlangs) which must be serviced at an RDU is given by

$A = \lambda/\mu$ *(erlangs/subscriber)*

where $1/\mu$ is the average request duration.

We desire to provide enough channels (servers) between the CO and the RDU, such that the probability of no channel being available to service a request is below some set Grade of Service (GOS), typically .01. We assume that a request can be serviced by any available channel; however, if there are no available channels, the requestor goes away.[3]

3.2.1. Erlang B Formula

More precisely, we assume an M/M/k loss system with average arrival rate λ, average holding time μ, and k servers. For such a system, the probability of all K servers (channels) being busy follows the well-known Erlang B formula: [38]

$$P_K = \frac{\frac{A^K}{K!}}{\sum_{m=0}^{K} \frac{A^m}{m!}}$$

Note that the Erlang B forumla does not depend upon the distribution of holding times, only on their average duration. The Erlang B formula provides a conservative estimate of the number of servers necessary since all blocked calls are cleared; other methods involving queueing discipline assumptions find fewer servers are necessary for equal traffic densities.

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[3]This is usually referred to as a full availability, loss system. For alternative models which assume that the caller retries within a short time interval see [28]

3.2.2. Estimating the Traffic

We must estimate the offered traffic A in order to determine the number of necessary servers K given some predefined grade of service. As a consequence of the lack of any observed on-demand video service traffic patterns, we assume that VCR owners approximate the viewing habits of potential on-demand viewers in order to estimate the average offered video traffic. According to the AC Nielsen Co., in 1984 the average owner of a VCR will, three years after purchase, watch 42 minutes per week or .75 hours per week of video cassettes [11].

The term Erlang is used to denote the offered load of traffic in requests per unit time (usually hours) multiplied by the request holding time. Since the duration of most videos is well over one hour, we know the .75 hours per week viewing figure most likely represents some percentage of a video request and not several video requests of shorter duration at different times of the week. With this in mind, we assume that all subscribers will offer an average traffic load of .75 hours each each week. Thus,

$$A_{avg} = 0.75 \quad (hours/week)$$

Not all video requests will occur during the peak busy hour--only a percentage of the weekly average. Let PBV be the ratio of minutes watched during the peak busy hour to toal minutes viewed per week (in our model we assume 20% of the weekly minutes are viewed during the busy hour, *e.g.* 8:30pm - 9:30pm on a weekend night. This compares to a mere 0.59% if the traffic were uniformly distributed over the 168 hours in a week). Then,

$$A_{busy} = A_{avg} \times PBV \quad (erlangs/subscriber)$$

Our model allows for the possibility that there is more than one television in use in a household, each tuned to a different program. Hightower notes that some 15% of CATV subscribers have a second drop. In our model, we have assumed that second, third and fourth drops increase the total number of users by 20% over the base number of households subscribed. These additional drops are assumed to generate requests for on-demand service at half the rate of the primary drops. Thus,

$$A_{totbusy} = A_{avg} \times PBV \times TOTSUB \times 1.1 \quad (erlangs)$$

Where TOTSUB is the total number of subscribers to fiber-based services at a particular RDU. In our model, we consider a range of values for A_{avg} between .75 - 3 erlangs per week. Given $A_{totbusy}$, we use tables of Erlang B values to derive the number of channels k necessary to meet a grade of service objective P_k.

3.3. Central Office Star

The simple star model uses switching and channelization quite similar to the active double star. The principal difference is that video switching takes place only at the CO, and a fiber runs directly from the CO to the subscriber's premises.

The CO is assumed to provide up to four 150 MBPS video channels to each subscriber. These channels are multiplexed onto a single fiber for each subscriber along with N-ISDN traffic for voice; wavelength division multiplexing allows the use of the same fiber for the return N-ISDN channel. In this

model, loop plant is not dependent on the level of Video-On-Demand service requests.

Equipment at the subscriber's premises is the same as for the active double star.

3.4. Passive Double Star

The third model we have analyzed in detail is the Passive Double Star. As described in Section 2.1.5, in the passive double star architecture, video signals for several subscribers are multiplexed onto a feeder fiber from the central office. At the RDU, a passive optical splitter replicates the combined signals onto *h* distribution fibers which carry them to network termination equipment (NTE) on the subscriber's premises. The NTE then demultiplexes the signals and presents the subscriber with his particular selection.

The number of households, *h*, which can be served from one feeder fiber depends upon two factors: the number of distinct video channels, *M* which can be carried on the fiber, and the statistics of viewing which determine the number of distinct channels *D* needed to service a group of *h* subscribers with grade of service α.

In the active double star design, the video channel rate was set at 150 Mbps in order to minimize the cost of video codecs. Multiplexors on the subscribers premises were limited to 600 Mbps. If these rates were applied to the passive double star, only four distinct channels could be provided by one fiber from the central office. Increasing the data rate on the fiber would require more costly demultiplexors in the subscriber's network termination equipment. A better approach would be to use moderately more costly codecs to reduce the video channel rate to 45 Mbps, while keeping the TDM rate at about 565 Mbps. While 45 Mbps is adequate for NTSC video signals, it may be inadequate for EQTV or HDTV. Nevertheless, this architecture economizes substantially on fiber by comparison with a single star, while minimizing the cost of equipment in the RDU. [22] Moreover, it does not require the development of video switches capable of operating at 150 Mbps rates. This approach can be viewed as one which is more easily achievable with current technology, while potentially more limiting in terms of future demands for HDTV.[4]

3.4.1. Households per Fiber

A fiber running at 565 Mbps with 45 Mbps per video channel has a capacity of 12 channels. How many households can be served by these 12 channels? Our first inclination was to follow the suggestion of Hightower [21] and attempt to analyze the statistics of video viewing. Recognizing that multiple households might desire to watch the same network programming, and that they could all be served from the same channel, one might attempt to calculate how many households *h* can actually be served by *M* channels with grade of service α. An analysis along these lines, using viewer statistics from A.C. Neilsen, [32] suggested that 12 channels might actually be adequate for up to 22 households with α=.01.

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[4]It is possible, of course, that the development of coherent modulation and detection technology will, in the future, make it economical to use wave length division multiplexing together with a passive star architecture to provide higher channel rates to each subscriber. Thus, the passive star physical network may well prove readily adaptable to 21st century technology.

Upon reflection, however, we observed that most CATV viewers from time to time scan most or all of the available channels, for example during network commercials. To the extent that three viewers of the same network program decide to scan the channels at the same time but in a different order, it takes not one but three distinct channels on the fiber to insure their ability to do so, despite the fact that most of the time one channel is sufficient. Since it seems unlikely from a marketing perspective that a system builder can afford to deny customers the right to "spin the dial", we are left with the conclusion that there is no opportunity for gain due to call statistics.

Thus, if M is the number of channels per fiber, and S is the fraction of additional channels per household which will be viewed concurrently with the primary connection, then $h = M/(1+S)$.

4. Results

We have run our model using the basic assumptions detailed above, together with a few sensitivity analyses in an attempt to better understand the economics of a fiber optic residential subscriber network.

4.1. Active Double Star

A key question, of course, is the total capital cost per subscriber to provide fiber-based services. We focus here on the *incremental* capital that must be invested to provide service over fiber as opposed to copper, and to provide video as well as voice. Thus we include all investments in fiber loop plant and new investments at the CO to support video switching. As noted earlier, we consider the costs of narrowband ISDN switching as sunk, and therefore they are not included.

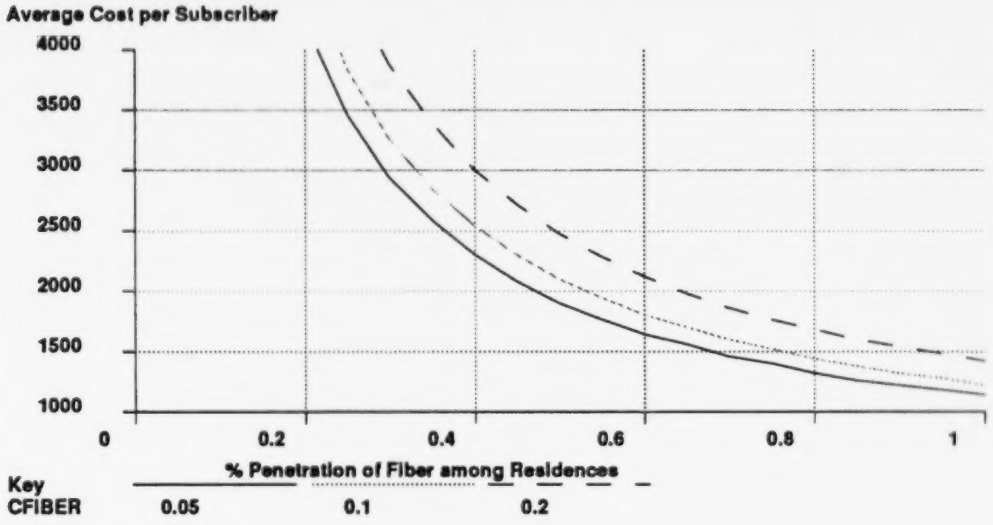
In practice, much of the capital must be invested up-front, before it is known how many residences will choose to subscribe. Consequently, the cost per subscriber depends strongly on the assumed penetration rate. Figure 4-1 shows the average cost per subscriber as a function of the percent penetration, for various estimates of fiber cost per meter. We have assumed 1.5 hours of video on demand viewing per subscriber per week.

Several previous studies have suggested that capital costs must be in the range of $1000 - 2000 for a FORSN to be viable. These results suggest that this range can be achieved, but only if there is substantial penetration of the targeted neighborhood.

Some insight can be gained by examining the relative contribution from several components of the cost. Figure 4-2, calculated on the basis of 60% penetration, shows that the largest component by far is the distribution loop, followed by the RDU equipment costs. Active switching at the RDU dramatically reduces the need for feeder fibers, which thus contribute only a small portion to the total cost. CO costs include loop termination costs plus only those minimal investments in switching which go beyond what would be in place to supply N-ISDN service.

As noted earlier, distribution loop costs are sensitive to assumptions about population density. Figure 4-3 shows how distribution loop costs change if the lot sizes and typical block lengths are adjusted to

Figure 4-1: Average Cost per Subscriber for Active Double Star



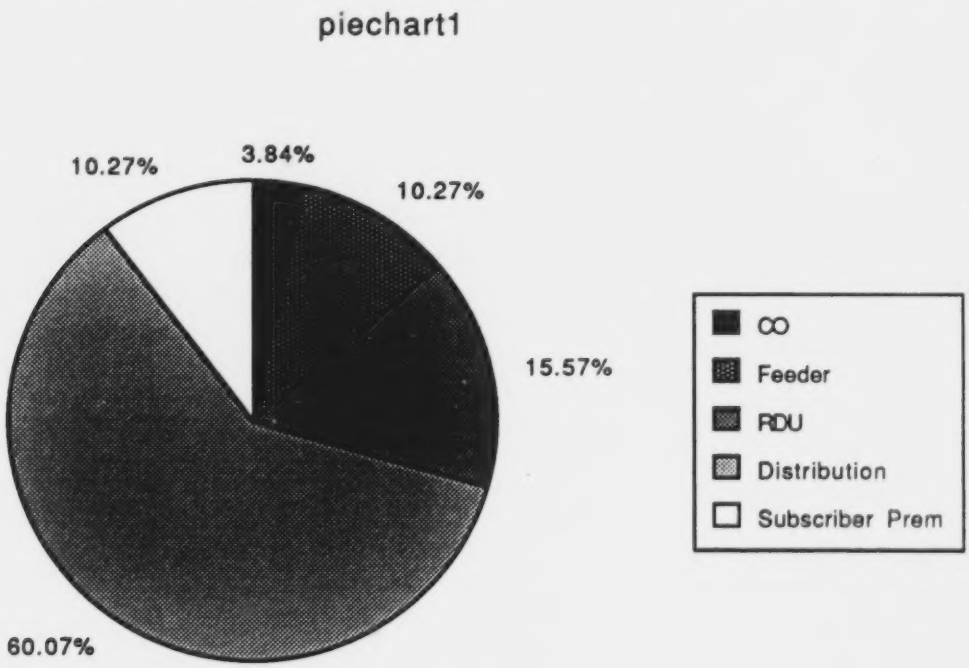
correspond to 75, 100 and 150 houses per street mile.

At an estimated cost of $45 each, the wavelength division multiplexors used in the distribution loop are comparable in cost to running an extra fiber to each subscriber, at least for the lower values of fiber cost. However, given our assumption that fiber must be laid before the ultimate penetration is known, the use of WDMs substitutes a variable cost for a fixed cost. Thus, the savings is even more significant if penetration remains low (Figure 4-4).

4.1.1. On Demand Video

While most of the loop plant varies only with the number of subscribers, an increase in demand for unique video programs requires additional investment in the feeder plant and video switching. We have used our model to calculate the incremental capital cost per subscriber that would result from an increase of one erlang per subscriber in the average use of the network for on-demand video (Figure 4-5). An increase of one erlang in average weekly viewing implies 52 additional revenue generating hours per year to recover this capital cost. Thus an incremental capital cost of $50 can be recovered in three years through a charge of only $.33/hour for on-demand video service This cost is likely to be dwarfed by the cost of a video jukebox, and by royalty payments to program copyrightholders. [23] Viewed as an incremental cost above a base cost for a CATV-like service, on-demand video can be provided for a relatively low communications cost.

Figure 4-2: Total Cost Distribution at 60% Penetration



4.2. Switched Star

The active double star model employs electronics at the RDU in order to reduce dramatically the amount of fiber which must be installed by comparison with the single switched star. Equally importantly, in an environment of uncertain penetration, the active double star reduces fixed investment in fiber plant in favor of incremental investment in switching. Even at 100% penetration and a very low assumed cost for fiber, it appears that the double star is a superior solution (Figure 4-6).

4.3. Passive Double Star

Hightower of BellSouth has proposed a passive double star architecture. Our analysis suggests that such an architecture does not offer substantial savings over other designs. Compared to the double star, the passive star uses more feeder fibers; in the distribution portion, installation costs dominate, and thus savings in fiber over the double star are less significant.

To be at all competitive with the double star, we must assume either a low bit rate for video, *e.g.* 45 Mbps, which is incompatible with future HDTV; or assume that by the time the demand for HDTV materializes, system capacity will have increased either through the use of coherent modulation and

Figure 4-3: Average Distribution Loop Cost versus Penetration by Households per Mile

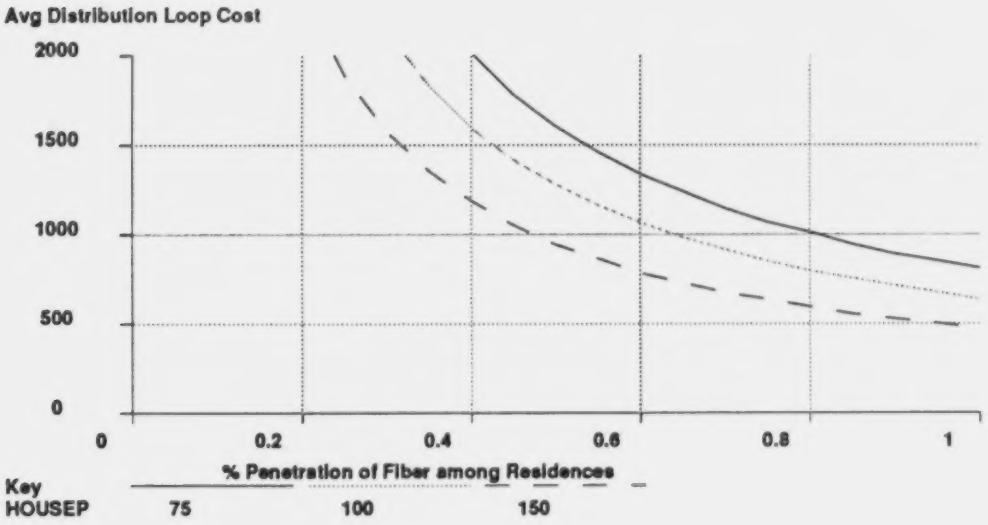
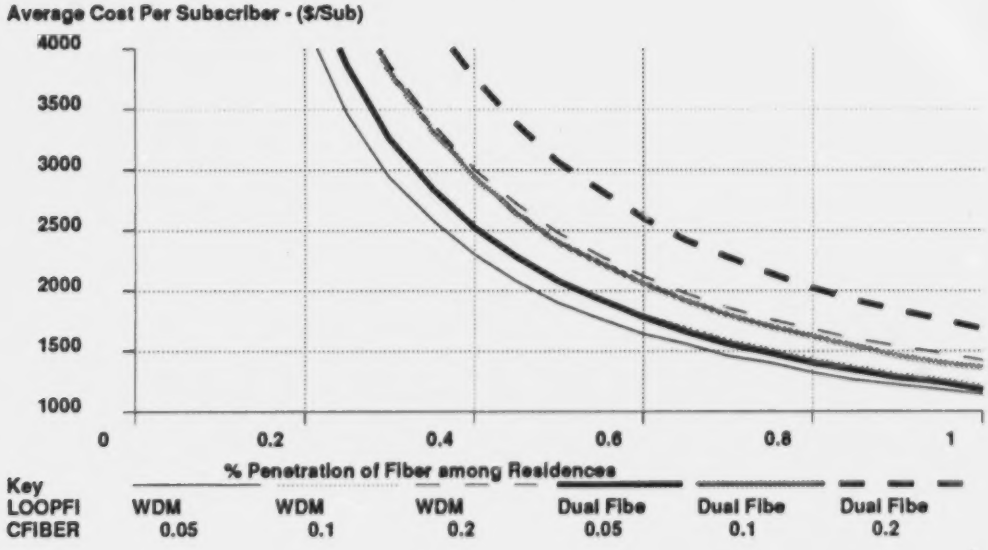


Figure 4-4: Total System Cost versus Penetration With WDM versus Dual Fibers



detection, or through the availability of low cost electro-optics and multiplexors operating at Gbps speeds, which allow a shift to 150 Mbps channels with no loss of capacity.

Figure 4-5: Incremental Capital Costs for On-Demand Video

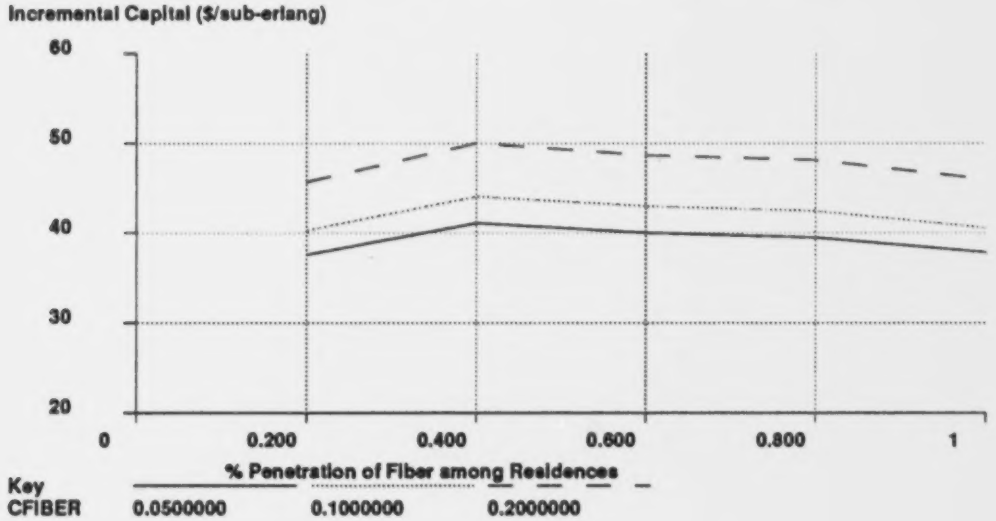


Figure 4-6: Average Cost Per Subscriber for Switched Star from CO

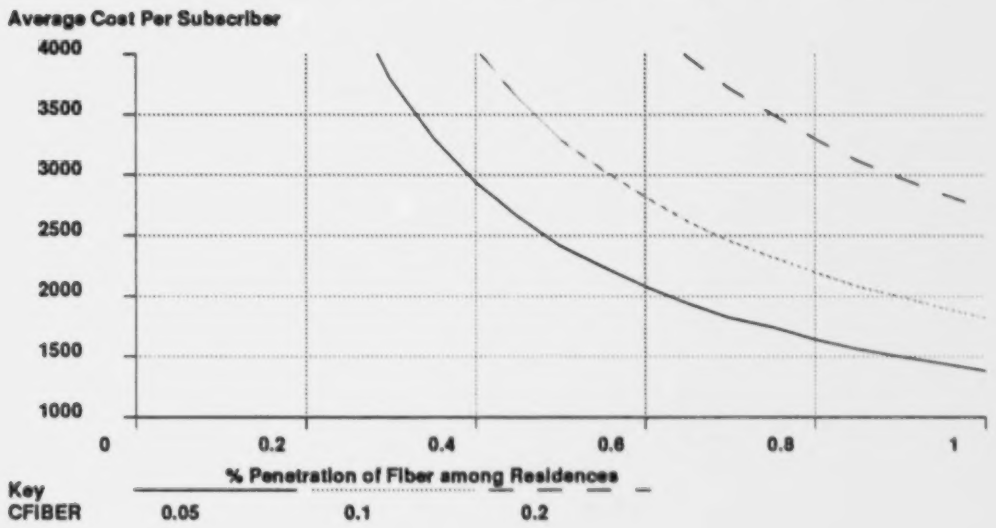
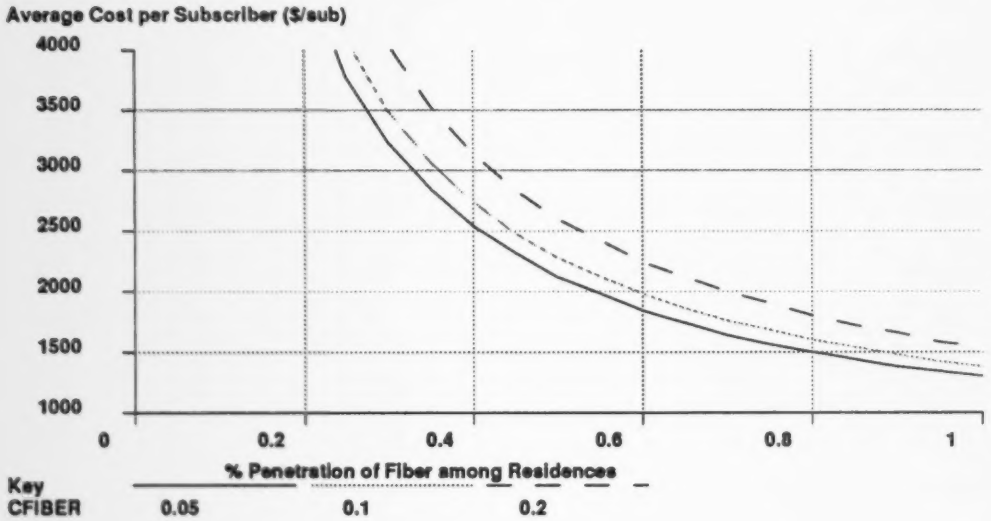


Figure 4-7: Average cost per subscriber for passive star using TDM



5. Conclusions

There are a number of conclusions we can draw from this preliminary analysis of fiber optic residential subscriber networks. First, it is clear that running fiber to the home, even assuming significant future reductions in component costs, is likely to remain more expensive than copper, where current loop plant costs are roughly $700 per subscriber. [21] If we are to see the introduction of a FORSN, it must be justified on the basis of additional revenue producing services, such as the delivery of entertainment video.

Point number one notwithstanding, our analysis suggests that a fiber optic network capable of providing both voice and video services to the home can be constructed for less than $1500-$2000 per subscriber. This brings it into the range of the combined cost of a CATV and telephone network, but having far greater functionality.

Third, there exist a number of architectures which reduce the amount of fiber required in favor of remote electronics or optical equipment. To the extent that electronics costs can be reduced to the levels we project, such designs can significantly reduce the total cost of the loop plant. For example, in the active double star model, fiber costs account for less than 25% of total loop plant costs. Thus, we need not achieve fiber production costs greatly below those now attainable in order to realize an economical FORSN.

Fourth, the high installation costs for fiber argue for installing adequate capacity at the beginning to

handle all subscribers in a serving area. Yet, it is unlikely that a FORSN, any more than CATV, will succeed in achieving 100% or even 70% penetration. In order to minimize the initial fixed capital investment, and the resultant economic risk that usage might not materialize at forecasted rates, it is desireable to select an architecture which trades fixed costs for equipment costs which are only incurred on an as-needed basis.

Fifth, the use of separate wavelengths to carry signals in both directions over a single fiber appears preferable to using dual fibers even under the most favorable assumptions regarding fiber cost.

Sixth, an architecture based on passive splitters is comparable to the active double star, which requires more untested electronics. However, pending the development of coherent modulation and detection techniques, or inexpensive components operating at Gbps speeds, the architecture we have modeled is limited to the carriage of NTSC as opposed to EQTV or HDTV signals. A judgement as to when support for the latter is required relative to when improved electro-optics will appear is needed to assess the importance of this limitation. None of our models include the equipment necessary for upstream video; however, a preliminary examination suggests that it will be far more difficult to upgrade a passive star architecture to support upstream video (*e.g.* for videotelephony) then to upgrade the single or double switched star configurations. Finally, the passive double star has a potential privacy problem since the signals for several households are carried on the fiber coming into each home. These signals are demultiplexed in the network circuit terminating equipment (NCTE) and only the signal destined for the particular home is passed to the codec. Security would be less of a problem, though by no means eliminated as an issue, if the NCTE could be treated as carrier rather than customer equipment, allowing the carrier to guarantee its integrity. Such a designation runs against current trends in FCC rulemaking. [13]

5.1. Policy Implications

These engineering and economic conclusions have a number of policy implications.

If the success of a FORSN requires revenues from the carriage of entertainment video, then we can expect intense lobbying from the local exchange carriers (LECS) to ease the restrictions which currently restrict their entry into this market. [19] The FCC has already announced its intention to reconsider the cross-ownership rules which ban LECs from owning cable operations in their territory. We can also expect that the entry of the LECs into video carriage will raise again the question of whether video signal distributors should be treated as publishers or as common carriers. [34]

Second, the high ratio of fixed to variable costs poses problems in terms of accounting for investments in--and pricing of services provided by--a FORSN. Given the relatively high ratio of fixed to variable costs for a FORSN, there is a risk that LECs will invest in fiber installation, only to find that penetration remains stalled at 20 or 30%. Under such circumstances, there may well be a tendancy to attempt to distribute the costs of such investment over all local telephone ratepayers, including those who subscribe only to more traditional copper plant based services.

Whether or not this is desireable as a policy matter is certainly open to debate. Some would argue that it is an appropriate way to encourage the introduction of new technology which will ultimately become universal. Others might take the position that only subscribers of the new fiber-based services should bear the costs of fiber installation. If the latter view is taken, estimates of future penetration rates will be a critical element of debates over the proper "cost" per subscriber of the loop plant. Optimistic estimates of penetration can lead to underpricing, and either substantial under-recovery of capital investment, or a shift of the capital costs to other ratepayers. The latter outcome will be difficult to avoid, especially if fiber installation is lumped with other investments in loop plant. As analyzed here, a FORSN clearly falls under the category of a "basic" service. As such, investments in fiber in the local loop are included for ratemaking purposes with investments in copper loop plant. Attempts to separate investment in a FORSN so as to avoid these problems will likely founder on the inability to distinguish between fiber installed in anticipation of eventual video delivery, and fiber installed today to reduce the cost of copper in the loop plant through multiplexing.

A State Public Utility Commission faced with a request by the local exchange carrier for a certificate of "public intrest convenience and necessity" to construct a FORSN has a difficult decision to make. The PUC's burden can be eased if there is some way to shift the risk of failure away from the POTS ratepayer.

The LEC can better its chances for PUC approval by engaging the local CATV franchise in a joint venture. A long term contract with a cable operator to provide video transport services over a FORSN shifts the subscriber penetration risk from the regulated PUC to the unregulated cable franchise. However, a FORSN threatens the cable operators's franchise monopoly, for it makes it possible for there to be many sources for video programming. Once a two-way switched video network is in place, any small businessman with a VCR and a few tapes can become a source for showing video on demand. Indeed, we may well see the development of the video equivalent of Computer Bulletin Board Systems: small scale providers of video information retrieval operated on a non-profit basis by individuals or clubs. Unlike the current voice switching systems, video switching systems will be designed from the beginning to replicate a single signal onto many lines, a necessary capability for the delivery of distributive video. Such a capability will enable every subscriber to become a potential broadcaster--limited only by the problems of identifying and marketing to an audience.

Finally, if the PUCs were to move from overall rate of return regulation to a price cap on basic voice service, then the risk of the investment in a FORSN can be shifted to the shareholders of the LEC. [29] Since revenue from POTS is capped, any losses which result from a failure to correctly guage the market for a FORSN cannot be passed on to the POTS ratepayer. By the same token, the LEC would then be in a position to reap fully the rewards of establishing a successful FORSN.

In sum, the broadband ISDN threatens to abolish forever the distinction between point to point and mass media, and force a collision among two long separated traditions of public policy and regulation.

A. COMPLETE MODEL LISTINGS

The following constitutes the full specification of the models reported on, taken directly from the input specification to the DEMOS modelling system.

Demos allows for a hierarchy of models and submodels, to simplify complex model building. The three architectures analyzed consist of the following component submodels:

- Active Double Star
  - Fiber
  - Demand
  - Electronics
  - Cable
- Central Office Star
  - Star
  - Demand
  - Electronics
  - Cable
- Passive Double Star
  - Fibershare
  - Demand
  - Electronics
  - Cable

A.1. Electronics

{ From Demos User ms6b , Demos Project FIBERSHARE at Mon Nov 23 16:14:24}

Model Electronics
Description: Low-level model containing a pool of electronic's cost component variables necessary for constructing the various architectures.
Contains: Variable Muxcoststan, Variable Mccswitch, Variable Cslic, Variable Csubmux, Variable Sliccap, Variable Cstage1, Variable Subboard, Variable Switchsize, Variable Switchcard, Variable Cswitchcard, Variable Subchan, Variable Cmuxbase, Variable Claser, Variable Capd, Variable Cled, Variable Cpin, Variable Csplitter, Variable Claser.wdm, Variable Wdmchan, Variable Cisdnmux, Variable Ds3mux, Variable Clambda, Variable Cisdn, Variable Csubcodec, Variable Csubscribmux, Function Int, Function Rounddown, Variable Currentled, Variable Currentpin
Author: Sirbu, et.al.
Date: Fri Apr 10 11:32:17
Savedate: Mon Nov 23 16:14:21

Variable Muxcoststan
Title: Standard rate mux cost
Units: $/channel
Description: Cost of multiplexing the 150Mb/s standard channel - inexpensive function due to SONET bit interleaving pattern and the use of inexpensive chips
Definition: 10

Variable Mccswitch
Title: Marginal Cost of CO Switch
Units: $/sub
Description: Marginal cost of the central office switch per subsciber - does not include common control considerations, which are considered in the cost of the voice CO switch (see variable cisdnco).
Definition: 25

Variable Cslic

Title: Cost of Subscriber Line Interface Card
Units: $/card
Description: Cost of SLIC which is shared by four subscribers (denoted by the variable SLICcap for SLIC capacity). Chip holds four electro-optic devices, four 150 to 600 Mb/s multiplexers (at $5/channel), one 16 by 16 switching chip at $5, and a board cost of $150 reflecting other circuitry costs.
Definition: SLICcap*(cled+csubmux)+cstage1+subboard

Variable Csubmux
Title: Cost of Subscriber Channel Mux
Units: $/sub
Description: Cost of the chip to multiplex four 150Mb/s channels into one 600 Mb/s stream to the subscriber
Definition: 5

Variable Sliccap
Title: SLIC Capacity
Units: sub/card
Description: Number of subscribers served per SLIC
Definition: 4

Variable Cstage1
Title: First Stage Subscriber Switch
Units: $/chip
Description: Cost of the first stage switch on the SLIC necessary to switch each video channel to the appropriate subscriber
Definition: 5

Variable Subboard
Title: Cost of SLIC board
Units: $/board
Description: Cost of the SLIC board
Definition: 150

Variable Switchsize
Title: Subscribers Served per Switch Card
Units: sub/card
Description: Number of subscribers served by each card. A 64 squared chip can serve 16 customers assuming four channels per customer.
Definition: rounddown(switchcard/subchan)

Variable Switchcard
Title: Input/Output Channels per Switch Card
Units: channels/card
Description: Number of input or output channels (assuming a square chip) per switch card, we are assuming a 64 X 64 video switch card is physically possible (enough room on the card for circuitry, etc...)
Definition: 64

Variable Cswitchcard
Title: Cost of Switch Card
Units: $/card
Description: Cost for one switch card which circuit switches 64 video channels
Definition: 200

Variable Subchan
Title: Channels per Subscriber
Units: chan/sub
Description: number of channels provided to each subscriber
Definition: 4

Variable Cmuxbase
Title: Base cost of a multiplexer
Units: $/feed fiber
Description: Base cost per fiber of a multiplexer
Definition: 1000

Variable Claser
Title: Cost of laser transmitter
Units: dollars/laser
Description: Cost of laser transmitter to convert electrical to optical signals
Definition: 100

Variable Capd
Title: Cost of Avalance Photodiode
Units: dollars/apd
Description: Cost of avalanche photodiode detectors to convert optical to electrical signals
Definition: 100

Variable Cled
Title: Cost of LED
Units: dollars/LED
Description: Cost of Light Emitting Diode optical transmitter
Definition: 25

Variable Cpin
Title: Cost of PIN diodes
Units: dollars/diode
Description: Cost of PIN diode optical detectors for use with LEDs on distribution drops.
Definition: 25

Variable Csplitter
Title: Cost of optical splitter
Units: dollars/port
Description: Cost of an optical splitter per port to send an identical optical signal out multiple fibers
Definition: 45

Variable Claser.wdm
Title: Cost of laser transmitters
Units: dollars/laser
Description: Cost of laser transmitters using WDM to convert electrical to optical signals
Definition: 125*wdmchan

Variable Wdmchan
Title: WDM Channels
Units: channels/fiber
Description: Number of channels that are wavelength divisioned multiplexed onto one fiber
Definition: 20

Variable Cisdnmux
Title: Cost of ISDN multiplexing
Units: $/channel
Description: Cost per channel of multiplexing ISDN channels into DS3 streams of information. Today's cost of complete DS3 system is $25,000 (Kerner) or $37 per channel; assume reduction to roughly $20 per channel in future.
Definition: 20

Variable Ds3mux
Title: DS3 multiplexor
Units: $

Description: Used at central office to mux/demultiplex ISDN traffic going between CO and RDU. Assume T1 rate lines into and out of NISDN switch, muxed onto a single feeder fiber at approximatley DS3 rate. Current cost is $11000. Assume reduction to $5000 in future.
Definition: 5000

Variable Clambda
Title: Cost of WDM coupler
Units: $/coupler
Description: Cost of WDM coupler - cost of coupler with just one port
Definition: 45

Variable Cisdn
Title: Capacity costs
Units: $/sub
Description: Cost of ISDN components located at the central office - represents the average cost per line at the central office for a digital switch.
Definition: 200

Variable Csubcodec
Title: Subscriber Codec
Units: $/codec
Description: Digital to analog converter needed for video signals. Assumed three chip implementation; cf. Andrich '87.
Definition: 20

Variable Csubscribmux
Title: Demultiplexor part of NT1.
Units: $
Description: Cost of the subscriber demultiplexing and channel selection part of the NT1 equipment. Provides T interface for N-ISDN. Assumed to be one card; cf Andrich '87.
Definition: 35

Function Int(x)
Description: The smallest integer >= x
Definition: round(x+0.4999999)

Function Rounddown(x)
Description: The largest integer <= x
Definition: round(x-0.4999999)

Variable Currentled
Title: Current LED Cost
Units: $
Description: Current cost of an LED source for use with the SLC 96
Definition: 50

Variable Currentpin
Title: FET
Units: $
Description: Current cost of a PIN-FET photodiode used with the SLC 96
Definition: 50

Close Electronics

A.2. Cable

{ From Demos User ms6b , Demos Project FIBERSHARE at Mon Nov 23 16:14:36}

Model Cable
Description: Low-level model containing the cable and cable installation variables for use in construction of the different network architectures.
Contains: Variable Subinstall, Variable Cfiber, Variable Sheath, Variable Cconn, Variable Contime, Variable Wage, Variable Vaultcost, Variable Looplength, Variable Ccopper, Variable Copperconn, Variable Copperinstal, Variable Currentfiber, Variable Currentconne, Variable Cinstall, Variable Avgblock, Variable Blockdensity, Variable Cabsize, Variable Streetside, Variable Feedduct, Variable Distduct, Variable Cdrop, Variable Csplice, Variable Cterminal, Variable Feedercable, Variable Ddist, Variable Lotfront, Variable Streetwidth, Variable Ddrop, Variable Subperkm, Variable Housepermile, Variable Sharedrop
Author: Sirbu et. al.
Date: Fri Apr 10 11:43:25
Inobjs: Kind Variable
Savedate: Mon Nov 23 16:14:35
Needs: Model Demand, Model Electronics

Variable Subinstall
Title: Installation cost at subscriber site
Units: $/subscriber
Description: Installation cost at the subscriber
Definition: 200

Variable Cfiber
Title: cost of fiber
Units: dollars/fiber-meter
Description: cost of individual strands of single mode fiber, per meter
Definition: [.05,.1,.2]

Variable Sheath
Title: Fixed $/m for multi-fiber cable
Units: dollars/cable-meter
Description: Fixed cost (independent of number of strands) for a multi-fiber cable, per meter
Definition: 0.10

Variable Cconn
Title: Connector cost
Units: dollars/connector
Description: Cost of fiber-optic connectors to connect between fiber and the electro-optics. Assume cost of $15/biconic connector plus the labor cost - see Kaiser notes for complexities associated with the connector - but no costs.
Definition: 15 + contime*wage

Variable Contime
Title: Connection Time
Units: hours
Description: Time to perform one connection using single mode fibers. Assume 15 minutes per connection (See Garbanati)
Definition: 0.25

Variable Wage
Title: Wage rate
Units: $/loaded hour
Description: Wage rate for craft to perform connections (See Garbanati)
Definition: 50

Variable Vaultcost

Title: Vault cost
Units: dollars/vault
Description: Fixed cost of a remote, enviromentally protected enclosure for remote switching gear. Assume value of $55K (See Notes from Shirley)
Definition: 55K

Variable Looplength
Title: Looplength distribution
Units: meters
Description: probability distribution of loop length in meters. Taken from hightower86a
Definition: fractiles([0,1212,2121,3030,3636,4242,4848,5757,6969,9090,20606])

Variable Ccopper
Title: Copper Wire Cost
Units: $
Description: Cost of 24 gauge wire per meter bundled in 50 wire cables
Definition: [.023, .075]

Variable Copperconn
Title: Copper Connect Costs
Units: $/connection
Description: Cost to connect copper wire pair to the RDU
Definition: 20

Variable Copperinstal
Title: Copper Installation Costs
Units: $/installation
Description: Cost to install copper wire pair to the household
Definition: 140

Variable Currentfiber
Title: Current SM Fiber Costs
Units: $/meter
Description: Current costs of SM fiber
Definition: .25

Variable Currentconne
Title: Current connector Costs
Units: $/connector
Description: Current costs of SM fiber connector, assumes connector costs $100 and it takes 15 minutes at $50/hour labor to connect per fiber
Definition: 115

Variable Cinstall
Title: Feeder cable installation cost
Units: $/meter
Description: The average installation cost for fiber cable, obtained assuming a weighted average of estimates for duicted, direct buried, and urban installation.
Definition: 10.52

Variable Avgblock
Title: Average Block Length
Units: meters
Description: Average length of a residential block; assumed in this model to be approximately 500 feet, or about 150 meters.
Definition: 6*1620/housepermile*2

Variable Blockdensity
Title: Density of living units per block
Units: units/block

Description: Average number of living units per block, each block assumed to be a square. Note that each side of the block has on average 6 living units.
Definition: 24

Variable Cabsize
Title: Distribution Loop Cable Size
Units: fibers/cable
Description: Size of the fiber cable which will be installed in the distribution portion of the network
Definition: 36

Variable Streetside
Title: Number of Blocks in Service Area
Units: streets
Description: If we assume the service area consists of a square grid of blocks, then, given the number of living units per square side, we can determine how many square blocks are necessary to hold 'res' units (number was calculated by dividing the square into four sections by drawing two diagonals and then multiplying the result by 4)
Definition: 4*int((res/4)/(rounddown((avgblock-streetwidth)/lotfront)*2))

Variable Feedduct
Title: Inner Duct Cost for use with Feeder Cable
Units: $/meter
Description: Cost of the inner duct cable which carries the feeder fibers of size equal to multiples of FEEDERCABLE.
Definition: 1.15
Data_source: Greg Dobrich, CMU Telecom department

Variable Distduct
Title: Inner Duct Cable Costs
Units: $/meter
Description: Cost of the inner duct cable which carries the distribution fiber of size CABSIZE.
Definition: .75

Variable Cdrop
Title: Drop Cost
Units: $/drop
Description: Cost of the final drop portion of the network, assumes that final trenching is approximately $5.75/meter, average drop length is 30 meters, a more durable sheath for the three fibers running running between the terminal (located in a manhole) to the house, which costs $.75 more than normal sheath. The distribution fiber terminates at a terminal, where it is spliced to the drop portion.
Definition: csplice+ddrop*(3*cfiber+(sheath+.75)+5.75)
Data_source: Trenching costs from Garbanati, Bellcore unpublished paper.

Variable Csplice
Title: Splice Cost
Units: $/splice
Description: Cost of single mode splice including labor and equipment. According to the source, the cost of ribbon splicing versus single fiber splicing is very similar, thus, we do not make any distinction
Definition: 20

Variable Cterminal
Title: Dist. Terminal Cost
Units: $/terminal
Description: Cost, including installation, of the terminal which houses the splices between the distribution and drop portions of the network. Assume two terminals per block.
Definition: 100

Variable Feedercable
Title: Feeder Cable Size

Units: fibers/cable
Description: Number of fibers assumed in one feeder cable inner duct. Feeder cables are assumed to come in multiples of 300 (similar to the existing available copper cables).
Definition: 100
Data_source: Based on discussions with Walter Schlagel, Bell of PA

Variable Ddist
Title: Distibution loop distance
Units: blocks
Description: Length of cable needed to cover 1000 residential units in a six square block configuration. Calculations suggest that out of a total of 84 block sides(variable STREETSIDES), an equivalent of 184 must be installed when considering overlapping sections. RDU is assumed to be located in the center of the service area
Definition: 184

Variable Lotfront
Title: Average Residental Lot Street Frontage
Units: meters
Description: Average frontange of lot size of the residential living unit. Falls out once you assume a value for block density and the net length of a block.
Definition: (avgblock-streetwidth)/(blockdensity/4)

Variable Streetwidth
Title: Street Width
Units: meters
Description: width of a typical street
Definition: 8.6
Data_source: Pittsburgh lot and block maps

Variable Ddrop
Title: Drop Length
Units: meters
Description: Length of drop from terminal to point of termination in subscriber residence. Assume 8 meters setback from street; lateral distance along street depends upon number of houses served per terminal. If we assume 2 terminals (manholes) per block, then average lateral distance from terminal to midpoint of lotfront is 1/8 the length of the block. Finally, must add, on average, half the street width.
Definition: 8 +1/8*(avgblock-streetwidth)+.5*streetwidth

Variable Subperkm
Title: Households per mile
Units: households/km
Description: The number of households per linear kilometer of street
Definition: [75, 100,150]
Data_source: Cable TV data

Variable Housepermile
Title: Households per mile
Units: households/mile
Description: The number of households per mile of street
Definition: 100
Data_source: Cable TV data

Variable Sharedrop
Title: Droplength
Units: meters

Description: Length of drop from terminal to point of termination in subscriber residence. Assume 8 meters setback from street; lateral distance along street depends upon number of houses served per terminal. If we assume 1 terminal (manhole) per block, then average lateral distance from terminal to midpoint of lotfront is 1/4 the length of the block. Finally, must add, on average, half the street width.
Definition: 8 +1/4*(avgblock-streetwidth)+.5*streetwidth

Close Cable

A.3. Demand

{ From Demos User ms6b , Demos Project FIBERSHARE at Mon Nov 23 16:14:12}

Model Demand
Description: A submodel which estimates the number of fibers required between the central office and a remote distribution unit for the active and passive double star architecture..
Contains: Variable Res, Variable Totsub, Variable J, Variable L, Variable Step, Variable Increment, Variable K, Variable Dvchan, Variable Pbv, Variable Avgtraf, Variable Odchanlow, Variable Odchanmed, Variable Odchanhigh, Variable Odchanarray, Variable Odchan, Variable Vdrate, Variable Fibercap, Variable Feedercap, Variable Channels, Variable Videochan, Variable Nfiber, Variable Traftab, Variable Totsubtab, Variable Secondsubs, Variable Second, Variable Sduf, Variable Interval, Variable Subrates, Variable Nfiber.tdm
Author: Sirbu, Ferrante, Reed
Savedate: Mon Nov 23 16:14:11
Needs: Model Electronics

Variable Res
Title: residences
Units: households
Description: total number of households served by one RDU who could subscribe to the services offered by the network
Definition: 1000

Variable Totsub
Title: total subscribers
Units: subscribers
Description: total number of subscribers based upon the percentage of residences receiving the fiber services
Definition: j*res

Variable J
Title: % Penetration of Fiber among Residences
Description: represents the percentage of residences served by one RDU who subscribe to the services offered by the network.[5]
Definition: sequence(k,increment)*step

Variable L
Title: Sub increment between 30-40%
Description: Dummy Variable
Definition: sequence(k+1,increment)-(k-1)

Variable Step
Title: Step Size
Description: Specification of the step size of the subscriber penetration
Definition: .05

Variable Increment
Title: Increment Spec
Description: Number of steps to be taken to determine subscriber penetration values
Definition: 20

Variable K
Description: Dummy variable - used to determine starting point of subscriber penetration percentage
Definition: 1

Variable Dvchan

---

[5]The sequence command generates a sequence of integers beginning with k and increasing by increment.

Title: distributed video channels
Units: video channels
Description: number of distributed video channels provided to the subscriber
Definition: 36

Variable Pbv
Title: peak busy viewing
Description: percentage of on-demand video viewing during the peak viewing period based on a weekly observation, value of .2 obtained from an informal survey of the percentage of video rentals occuring on a weekend evening at West Coast Video store
Definition: .2

Variable Avgtraf
Title: average traffic
Units: erlangs/subscriber
Description: average traffic offered per subscriber per week, value of .75 erlangs per week found in The Economist, Dec. 20, 1986
Definition: [.75,1.5,3]

Variable Odchanlow
Title: on-demand viewing channels
Description: maximum number of on-demand viewing channels designed for the system based upon a low estimate of average traffic.[6][7][8]Definition: linear(totsubtab,subscript(traftab,avgtraf,slice(avgtraf,avgtraf,1)),secondsubs)

Variable Odchanmed
Title: on-demand viewing channels
Description: maximum number of on-demand viewing channels designed for the system based upon a medium estimate of average traffic
Definition: linear(totsubtab,subscript(traftab,avgtraf,slice(avgtraf,avgtraf,2)),secondsubs)

Variable Odchanhigh
Title: on-demand viewing channels
Description: maximum number of on-demand viewing channels designed for the system based upon a high estimate of average traffic
Definition: linear(totsubtab,subscript(traftab,avgtraf,slice(avgtraf,avgtraf,3)),secondsubs)

Variable Odchanarray
Title: array of on-demand viewing channels
Description: range of on-demand viewing channels based upon different values of average traffic
Definition: [odchanlow,odchanmed,odchanhigh]

Variable Odchan
Title: on-demand viewing channels
Description: table of on-demand viewing channels as a function of the average traffic offered per subscriber
Definition: int(array(avgtraf,odchanarray))

Variable Vdrate
Title: Video bandwidth
Units: Mbits/sec

---

[6]The linear takes three parameters: a vector of x values, a vector of y values, y(x), and a value x_0. It's output is $y(x_0)$ determined by linear interpolation.~

[7]Slice(a,i,n): If a is an array of dimension m, one of whose indices is i, then slice produces an array of dimension m-1 produced by fixing i to be the n^{th} value of i.~

[8]subscript(a,i,x): similar to slice, but produces the subarray by fixing i at the index whose value corresponds to x

Description: standard bandwidth for a video signal, independent of the picture quality, used in the active double-star and the switched star
Definition: 150

Variable Fibercap
Title: Passive architecture fiber bit rate
Units: Mbits/sec
Description: total capacity provided by one fiber cable
Definition: 600

Variable Feedercap
Title: Feeder Fiber Capacity
Units: Mbps
Description: Capacity of feeder fiber in megabits per second.
Definition: 2400

Variable Channels
Title: Video channels per feeder fiber
Units: Channels/Feeder Fiber
Description: Number of channels (as determined by the subscriber line rate) per feeder fiber
Definition: rounddown(feedercap/vdrate)

Variable Videochan
Title: Peak video channels
Units: TV channels
Description: Peak video channels required between the CO and RDU based upon on-demand and distributed video traffic
Definition: odchan+dvchan

Variable Nfiber
Title: Feeder fibers required for video dist.
Units: fibers
Description: total number of fibers necessary between the CO and the RDU to provide downstream video services plus two fibers for full duplex N-ISDN services.
Definition: int(slice(videochan,j,increment)/channels)+2

Variable Traftab
Title: traffic table
Units: channels
Description: table of required channels for a given traffic load and grade of service equal to 0.01 using the Erlang B formula
Definition: table(avgtraf,totsubtab)(0, 13, 20, 28, 35, 42, 48, 55, 62, 68, 75, 83, 91, 99, 107, 115, 123, 131, 138, 146, 154, 162, 170, 178, 0, 20, 35, 48, 62, 75, 88, 100, 113, 126, 138, 154, 170, 185, 201, 216, 232, 247, 263, 278, 293, 309, 324, 340, 0, 35, 62, 88, 113, 138, 163, 188, 213, 238, 263, 293, 324, 354, 385, 415, 446, 476, 507, 537, 567, 597, 628, 658)

Variable Totsubtab
Title: range of subscribers
Units: subscribers
Description: array of subscribers (or allowed range of subscribers) used to construct traffic table
Definition: [0, 40, 80, 120, 160, 200, 240, 280, 320, 360, 400, 450, 500, 550, 600, 650, 700, 750, 800, 850, 900, 950, 1000, 1100]

Variable Secondsubs
Title: range of subscribers
Units: subscribers
Description: range of subscribers adjusted to reflect second drops
Definition: totsub*(1+second*sduf)

Variable Second

Title: Second drops
Description: percentage of second drops to subscribers (percentage of 15% obtained from article by Hightower in Globecom '86)
Definition: .2

Variable Sduf
Title: Second Drop Usage Factor
Description: Percent drop in on-demand video usage for the second drop
Definition: .5

Variable Interval
Title: Subscriber interval
Units: subscribers
Description: Number of subscribers between each calculated interval
Definition: slice(totsub,j,3)-slice(totsub,j,2)

Variable Subrates
Title: Subscriber line rate
Units: Mbits/sec
Description: subscriber line rate for the passive double-star and the switched star with shared resources architectures
Definition: [45,100]

Variable Nfiber.tdm
Title: total fibers between CO and RDU
Units: fibers
Description: total number of downstream feeder fibers (or equivalently, upstream fibers for N-ISDN)
Definition: int(secondsubs/rounddown(fibercap/subrates))

Close Demand

A.4. Fiber

{ From Demos User ms6b , Demos Project FIBER at Mon Nov 23 14:41:20}

{ System Variables with non-default values: }

Attribute Data_source
Inobjs: Kind Variable

AskAttribute Data_source,Variable,YES
Model Fiber
Description: Residential fiber optic local loop cost model for the active double-star architecture
Contains: Model Demand, Model Electronics, Model Cable, Variable Dfeed, Variable Cisdnco, Variable Cisdnrdu, Variable Cdist, Variable Cremswitch, Variable Cswitch, Variable Cmux, Variable Cline, Variable Cco, Variable Cfeed, Variable Crdu, Variable Csub, Variable Ctotal, Variable Avcost, Variable Marcost, Variable Cnt1, Variable Capcost, Variable Lriccapcost, Variable Avrdu, Variable Avdist, Variable Avfeed, Variable Avco, Variable Cwdm, Variable Cfeedcable, Variable Distcable, Variable Protection
Author: Sirbu et.al.
Date: Tue Mar 31 15:09:52
Savedate: Mon Nov 23 14:41:18
Needs: Model Demand, Model Electronics, Model Cable

Variable Dfeed
Title: feeder length
Units: meters
Description: Average distance from central office to active RDU. According to source, ratio of the mean feeder length to the mean working length is .97
Definition: .97*looplength
Data_source: "The LAST Bell System Subscriber Loop Survey", Telephony, October 5, 1987.

Variable Cisdnco
Title: NISDN interface at CO
Units: $
Description: Costs for interfacing fiber loop plant with existing N-ISDN switching.
Definition: ds3mux+cled+cpin

Variable Cisdnrdu
Title: Cost of ISDN at RDU
Units: $/RDU
Description: Cost of providing ISDN service for all subscribers over fiber
Definition: cisdnmux*totsub+cled+cpin

Variable Cdist
Title: Cost of distribution fiber plant
Units: dollars
Description: Total cost of distribution fiber plant from RDU to subscriber. Assumes fibers terminated with connectors at RDU up front. Assumes a square grid layout of blocks and 1000 living units; by actually laying out the distribution network using distribution fiber cables of size CABSIZE, it was found that 46 sides of the blocks must be cabled. See other variables in Model Cable for more detail.
Definition: res*(cconn+cdrop)+avgblock*(streetside*cinstall + ddist*(cfiber*cabsize + sheath+distduct)) + cterminal*streetside*2

Variable Cremswitch
Title: Remote video switch cost
Units: $/RDU
Description: Total cost of remote video switch, includes cost of line interface units for each feeder fiber, the size of the switching matrix as a function of the number of chips required, and subscriber line interface units which serve four customers per card.
Definition: int(totsub/switchsize)*cswitchcard+cslic*int(totsub/SLICcap)

Variable Cswitch
Title: CO Switch Costs
Units: dollars
Description: Cost of wideband square matrix switch located in the CO - serving only one RDU
Definition: mccswitch*totsub+int(videochan/switchcard)*cswitchcard

Variable Cmux
Title: Multiplexor cost
Units: $/feed fib
Description: Total cost of multiplexing per feeder fiber, assuming a large fixed cost for the card and small marginal cost per multiplexed channel
Definition: cmuxbase+muxcoststan*channels

Variable Cline
Title: Line Interface Unit
Units: $/LIU - feeder fiber
Description: Cost of the line interface unit which includes the electro-optics, demultiplexing, first stage switching functions (cost of which is a maximum of two 16 square chips, since the number of channels per feeder fiber will probably not be greater than 32). Assuming the board cost is absorbed in the base multiplexer cost..
Definition: capd+cmux+2*cstage1

Variable Cco
Title: Cost of central office plant
Units: dollars
Description: Total cost of central office equipment required for this architecture
Definition: cswitch+(cmux+claser)*(nfiber-2)+cisdnco

Variable Cfeed
Title: Total cost of feeder plant
Units: dollars
Description: Total cost of feeder fiber plant from CO to RDU including installation
Definition: (cinstall+cfeedcable)*dfeed+nfiber*2*cconn

Variable Crdu
Title: Total RDU cost
Units: $/RDU
Description: Total cost of equipment and vault at RDU site
Definition: vaultcost+cline*nfiber+cremswitch+cisdnrdu + cwdm

Variable Csub
Title: Total subscriber premises costs
Units: $
Description: Cost of all CPE and installation
Definition: totsub*cNT1

Variable Ctotal
Title: Total Cost
Units: $
Description: Total cost of all equipment and installation for an RDU serving area
Definition: cco+cfeed+crdu+cdist+csub

Variable Avcost
Title: Average Cost per subscriber
Units: $/subscriber
Description: Average cost per subscriber for all outside plant and CPE
Definition: ctotal/(totsub+1)

Variable Marcost
Title: Marginal cost

Units: $/sub
Description: Marginal cost of each additional subscriber to the fiber-based services.
Definition: (slice(ctotal,j,l)-slice(ctotal,j,l-1))/interval

Variable Cnt1
Title: customer interface unit
Units: $/sub
Description: customer interface unit (NT1/2 equivalent)
Definition: cled+cpin+cconn+clambda+csubscribmux+(1+second)*csubcodec

Variable Capcost
Title: Extra Capacity Costs
Units: $/erlang
Description: Additional cost of capacity necessary to support subscribers who demand 3 erlangs/week of video on-demand versus .75 erlangs/week
Definition: (slice(ctotal,avgtraf,3)-slice(ctotal,avgtraf,1))/(slice(avgtraf,avgtraf,3)-slice(avgtraf,avgtraf,1))

Variable Lriccapcost
Title: LRIC of Capacity
Units: $/sub-erlang
Description: Additional capacity cost per subscriber-erlang for an increase in demand for on-demand service
Definition: capcost/(totsub+1)

Variable Avrdu
Title: RDU cost per subscriber
Units: $/sub
Description: total RDU costs divided by number of subscribers served.
Definition: crdu/(totsub+1)

Variable Avdist
Title: distribution loop cost per subscriber
Units: $/sub
Description: total distribution plant (downstream of RDU) cost divided by number of subscribers
Definition: cdist/(totsub+1)

Variable Avfeed
Title: average cost of feeder plant per subscriber
Units: $/sub
Description: total cost of feeder plant divided by total subscribers
Definition: cfeed/(totsub+1)

Variable Avco
Title: average CO costs per subscriber (for double star)
Units: $/sub
Description: total CO costs in support of one RDU divided by total subscribers at that RDU
Definition: cco/(totsub+1)

Variable Cwdm
Title: Total cost of WDMs at RDU
Units: $
Description: Total cost of wavelength division muxes at RDU used on the subscriber drops.
Definition: totsub*clambda

Variable Cfeedcable
Title: Feeder Fiber Cable Costs
Units: $/meter
Description: Cost of a feeder fiber sized cable per meter, assuming that bi-directional fibers are not being used
Definition: int(nfiber/feedercable)*(feedercable*cfiber+sheath)+feedduct

Variable Distcable
Title: Inner Duct Cables
Units: cables
Description: Number of distribution cables (each carrying CABSIZE fibers) necessary to serve 1000 residential units.
Definition: 4*int((streetside/4)/int(cabsize/(protection*blockdensity/2)))

Variable Protection
Title: Protection factor
Description: Level of protection installed in the distribution portion of the network
Definition: 1.5

Close Fiber

A.5. Star

{ From Demos User ms6b , Demos Project STAR at Mon Nov 23 14:52:28}

{ System Variables with non-default values: }

Attribute Data_source
Inobjs: Kind Variable

AskAttribute Data_source,Variable,YES
Model Star
Description: Residential fiber optic local loop cost model
Contains: Model Demand, Model Cable, Variable Cswitch, Variable Cmux, Variable Cline, Variable Cco, Variable Cloop, Variable Cfeedcable, Variable Cdist, Variable Csub, Variable Ctotal, Variable Avcost, Variable Marcost, Variable Cnt1, Variable Avloop, Variable Cwdm, Variable Avco, Variable Cisdnco, Variable Dfeed, Variable Distcable, Variable Protection, Version Vgraph
Author: Sirbu et.al.
Date: Tue Mar 31 15:09:52
Savedate: Mon Nov 23 14:52:28
Needs: Model Demand, Model Electronics, Model Cable

Variable Cswitch
Title: CO Switch Costs
Units: dollars
Description: Cost of wideband square matrix switch located in the CO - serving only one RDU
Definition: mccswitch*totsub+totsub*(1+second)*cswitchcard/switchcard +cslic*int(totsub/SLICcap)

Variable Cmux
Title: Multiplexor cost
Units: $/feed fib
Description: Total cost of multiplexing per feeder fiber, assuming a large fixed cost for the card and small marginal cost per multiplexed channel
Definition: cmuxbase+muxcoststan*channels

Variable Cline
Title: Line Interface Unit
Units: $/LIU - feeder fiber
Description: Cost of the line interface unit which includes the electro-optics, demultiplexing, first stage switching functions (cost of which is a maximum of two 16 square chips, since the number of channels per feeder fiber will probably not be greater than 32). Assuming the board cost is absorbed in the base multiplexer cost..
Definition: capd+cmux+2*cstage1

Variable Cco
Title: Cost of central office plant
Units: dollars
Description: Total cost of central office equipment required for this architecture
Definition: cswitch+cisdnco+cwdm

Variable Cloop
Title: Total cost of loop plant
Units: dollars
Description: Total cost of loop fiber plant from CO to subscriber including installation
Definition: res*(2*cconn+cdrop)+(cinstall+cfeedcable)*dfeed+int(res*protection)*csplice+cdist

Variable Cfeedcable
Title: Feeder Fiber Cable Costs
Units: $/meter
Description: Cost of a feeder fiber sized cable per meter, assuming that bi-directional fibers are not being used (need two fibers per splitter - one for each direction)
Definition: int(res*protection/feedercable)*(feedercable*cfiber+sheath)+feedduct

Variable Cdist
Title: Cost of distribution fiber plant
Units: dollars
Description: Total cost of distribution fiber plant from RDU to subscriber. Assumes fibers terminated with connectors at RDU up front. Assumes a square grid layout of blocks and 1000 living units; by actually laying out the distribution network using distribution fiber cables of size CABSIZE, it was found that 46 sides of the blocks must be cabled. See other variables in Model Cable for more detail.
Definition: avgblock*(streetside*cinstall+ddist*(cfiber*cabsize+sheath*distduct))+cterminal*streetside*2

Variable Csub
Title: Total subscriber premises costs
Units: $
Description: Cost of all CPE and installation
Definition: totsub*cNT1

Variable Ctotal
Title: Total Cost
Units: $
Description: Total cost of all equipment and installation for an RDU serving area
Definition: cco+cloop+csub

Variable Avcost
Title: Average Cost per subscriber
Units: $/subscriber
Description: Average cost per subscriber for all outside plant and CPE
Definition: ctotal/(totsub+1)

Variable Marcost
Title: Marginal cost
Units: $/sub
Description: Marginal cost of each additional subscriber to the fiber-based services.
Definition: (slice(ctotal,j,l)-slice(ctotal,j,l-1))/interval

Variable Cnt1
Title: customer interface unit
Units: $/sub
Description: customer interface unit (NT1/2 equivalent)
Definition: cled+cpin+cconn+clambda+csubscribmux+(1+second)*csubcodec

Variable Avloop
Title: Average cost of loop plant per subscriber
Units: $/sub
Description: Total cost of loop plant divided by total subscribers
Definition: cloop/(totsub+1)

Variable Cwdm
Title: total cost of WDM's
Units: $
Description: cost of WDMs times the number used at one end.
Definition: totsub*clambda

Variable Avco
Title: average CO costs per subscriber (for double star)
Units: $/sub
Description: total CO costs in support of one RDU divided by total subscribers at that RDU
Definition: cco/(totsub+1)

Variable Cisdnco
Title: Cost of ISDN at CO
Units: $

Description: The only N-ISDN cost at CO is the detector for the upstream voice traffic. Since there is one fiber per household, no demultiplexing is needed, and the detected signal can be fed straight to the N-ISDN switch
Definition: cpin*totsub

Variable Dfeed
Title: Feeder Length
Units: meters
Description: Average distance of drop cable from the CO to point of divergence of the main cable. According to referenced source the ratio of mean working length to mean feeder length is .97
Definition: .97*looplength
Data_source: "The LAST Bell System Subscriber Loop Survey", Telephony, October 5, 1987.

Variable Distcable
Title: Inner Duct Cables
Units: cables
Description: Number of distribution cables (each carrying CABSIZE fibers) necessary to serve 1000 residential units.
Definition: 4*int((streetside/4)/int(cabsize/(protection*blockdensity/2)))

Variable Protection
Title: Protection factor
Description: Level of protection installed in the distribution portion of the network
Definition: 1.5

Version Vgraph
Description: system variables for creating graphs

Close Star

A.6. Fibershare

{ From Demos User ms6b , Demos Project FIBERSHARE at Mon Nov 23 16:14:06}

{ System Variables with non-default values: }

Attribute Data_source
Inobjs: Kind Variable

AskAttribute Data_source,Variable,YES
Model Fibershare
Description: Residential fiber optic local loop cost model for the passive double star architecture
Contains: Model Demand, Model Electronics, Model Cable, Variable Dfeed, Variable Muxcost, Variable Ccoder, Variable Cisdnco, Variable Cnt1.tdm, Variable Cmux.tdm, Variable Cswitch, Variable Cdist, Variable Crdu.tdm, Variable Cfeed.tdm, Variable Csub.tdm, Variable Cco.tdm, Variable Ctotal.tdm, Variable Avcost.tdm, Variable Marcost.tdm, Variable Cmuxbaseshar, Variable Plot, Variable Cfeedcable, Variable Terminal, Variable Distcable, Variable Protection, Variable Cdistcable, Variable Compresschan, Variable Cabsizeshare, Variable Clargecable, Variable Csmallcable, Variable Cdropshare, Variable Avdist
Author: Sirbu et.al.
Date: Tue Mar 31 15:09:52
Savedate: Mon Nov 23 16:14:06
Needs: Model Demand, Model Electronics, Model Cable

Variable Dfeed
Title: feeder length
Units: meters
Description: Average distance from central office to passive RDU. According to source, ratio of the mean working length to the mean feeder length is .97 Since we expect the distance to be a bit longer (less than 20 subscribers served per RDU), we assume ratio to be .99 in this architecture.
Definition: .97*looplength

Variable Muxcost
Title: Multiplexor cost
Units: dollars/channel
Description: cost per channel for a multiplexor for non-standard rates
Definition: table(subrates)(10,10)

Variable Ccoder
Title: Cost of coder
Units: dollars/coder
Description: Cost of coder for compression/decompression of video signals, assumed a coder is needed for each output channel of the CO switch as well as in each NT1/2 device
Definition: table(subrates)(50,25)

Variable Cisdnco
Title: Cost of ISDN at CO
Units: $
Description: The upstream traffic from N households was aggregated at the remote splitter and sent to the CO. Assume N<24, and that the aggregated traffic can be input as a T1 stream directly into ISDN switch. Then all that is needed is a detector for each incoming fiber.
Definition: cpin*nfiber.tdm

Variable Cnt1.tdm
Title: Network Termination Device
Units: $/device
Description: Network termination device required: consists of a WDM coupler,APD receiver, a TDM demultiplexer, and an ISDN card
Definition: cled+cpin+cconn+csubscribmux+(1+second)*(csubcodec+ccoder)

Variable Cmux.tdm

Title: Multiplexing Costs
Units: $
Description: Cost of time division multiplexing of signals for transmission
Definition: cmuxbaseshare+muxcost*compresschan

Variable Cswitch
Title: Wideband switch costs
Units: $
Description: Cost of wideband switch located in the CO
Definition: mccswitch*totsub+int(nfiber.tdm*compresschan)/switchcard*cswitchcard

Variable Cdist
Title: Cost of distribution fiber plant
Units: dollars
Description: Total cost of distribution fiber plant from RDU to subscriber. Assumes a square grid layout of blocks and 1000 living units; by actually laying out the distribution network using distribution fiber cables, it was found that 46 sides of the blocks must be cabled. See other variables in Model Cable for more detail.
Definition: res*(cconn+cdropshare)+cdistcable+terminal*streetside

Variable Crdu.tdm
Title: RDU cost
Units: $
Description: Cost of the RDU which consists of a downstream splitter for N-ISDN and video traffic and an upstream coupler for the returning N-ISDN traffic
Definition: int(slice(nfiber.tdm,j,increment)*2/feedercable)*feedercable*csplice

Variable Cfeed.tdm
Title: Total cost of feeder plant
Units: dollars
Description: Total cost of feeder fiber plant from CO to splitter including installation using TDM technology. We assume the splitter is located in the terminal placed inside the manholes situated at every block.
Definition: dfeed*(cfeedcable+cinstall)+4*cconn*slice(nfiber.tdm,j,increment)

Variable Csub.tdm
Title: Total subscriber premises costs
Units: $
Description: Cost of all CPE and installation
Definition: totsub*(subinstall+cNT1.tdm)

Variable Cco.tdm
Title: Cost of central office equipment
Units: $
Description: Total cost of equipment required in the central office to provide TDM signals
Definition: cswitch+(cmux.tdm+claser)*nfiber.tdm+cisdnco

Variable Ctotal.tdm
Title: Total Cost
Units: $
Description: Total cost of all equipment and installation
Definition: cco.tdm+cfeed.tdm+crdu.tdm+cdist+csub.tdm

Variable Avcost.tdm
Title: Average Cost per subscriber
Units: $/subscriber
Description: Average cost per subscriber for all outside plant and CPE using TDM technology
Definition: ctotal.tdm/(totsub+1)

Variable Marcost.tdm

Title: Marginal Cost
Units: $/sub
Description: Marginal cost for each additional subscriber to the fiber-based network services
Definition: (slice(ctotal.tdm,j,l)-slice(ctotal.tdm,j,l-1))/interval

Variable Cmuxbaseshar
Title: Base cost of a multiplexer
Units: $/feeder fiber
Description: Base cost per fiber of a multiplexer, assuming a 600Mb/s capacity for fiber will require CMOS technology and not GaAs chip technology.
Definition: 100

Variable Plot
Title: Average Cost per Subscriber
Units: $/Sub
Description: variable for producing graphs
Definition: mean slice(slice(avcost.tdm,subrates,1),avgtraf,2)

Variable Cfeedcable
Title: Feeder Fiber Cable Costs
Units: $/meter
Description: Cost of a feeder fiber sized cable per meter, assuming that bi-directional fibers are not being used (need two fibers per splitter - one for each direction)
Definition: int(slice(nfiber.tdm,j,increment)*2/feedercable)*(feedercable*cfiber+sheath)+feedduct

Variable Terminal
Title: Terminal Costs
Units: $/terminal
Description: Cost of the terminal situated in the manhole. We are assuming approximately one manhole per block. Contained in the metallic terminal is the passive splitter which will serve all those located on this side of the block.
Definition: cterminal+csplitter*compresschan*int((blockdensity/2)/compresschan)

Variable Distcable
Title: Inner Duct Cables
Units: cables
Description: Number of distribution cables (each carrying CABSIZE fibers) necessary to serve 1000 residential units.
Definition: 4*int((streetside/4)/int(cabsize/(protection*blockdensity/2)))

Variable Protection
Title: Protection factor
Description: Level of protection installed in the distribution portion of the network
Definition: 4

Variable Cdistcable
Title: Total Cost of Dist. Plant
Units: dollars
Description: Total cost of the distribution fiber plant from the RDU to the manhole nearest the subscriber. This cost assumes 1000 living units over six square blocks. Our calculations assume the existence of one splice point in the distribution area, through which approximately 70% of the fibers are installed.
Definition: avgblock*(streetside*cinstall+csmallcable+clargecable)

Variable Compresschan
Title: Compressed Channels
Units: channels/fiber
Description: Number of compressed video channels per fiber
Definition: rounddown(fibercap/subrates)

Variable Cabsizeshare

Title: Cable Size Using Passive Double Star
Units: fibers
Description: Assumes that the standard distribution cable size used in distribution loop corresponds to multiples of the typical protection factor which might be required. Cable serves at least 3 blocks.
Definition: protection*int((blockdensity/2)/compresschan)*3

Variable Clargecable
Title: Large cable costs
Units: $/meter
Description: larger cable is used to serve up to 6 blocks in series. Assumed to be twice as large (2*cabsizeshare) as the smaller cable.
Definition: 4*17*(cfiber*2*cabsizeshare+(sheath+distduct))

Variable Csmallcable
Title: Smaller Dist. Cables
Units: $/meter
Description: Cost of the small distribution cables assumed to be of size CABSIZESHARE. The number of 4*13 is obtained from actual calculations of the layout of the service area. We assume that each manhole needs CABSIZESHARE fibers running to it - the starting point of the cable is the RDU.
Definition: 4*13*(cfiber*cabsizeshare+sheath+distduct)

Variable Cdropshare
Title: Drop cost for passive star architecture
Units: $/drop
Description: Cost of the final drop portion of the network. Differs from cdrop used in other models because assume only one manhole
Definition: csplice+sharedrop*(3*cfiber+(sheath+.75)+5.75)

Variable Avdist
Title: Average dist loop cost
Units: $/sub
Definition: cdist/totsub

Close Fibershare

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COMPETITION IN THE LOCAL LOOP
Chair: William Taylor

Dennis Weisman: Default Capacity Tariffs: Smoothing the Transitional Regulatory Asymmetries in the Telecommunications Marketplace

This paper calls for the local companies to develop and tariff a new service known as Default Capacity. Specifically, it is proposed that facility bypassers pay flat rate default capacity charges to ensure the availability of back-up network capacity in the event of system failure or overflow during periods of peak utilization. While the emphasis here is on carrier access bypass, the logic underlying this proposal extends to all forms of competition within the local exchange, including local area bypass and shared tenant service (STS). These charges should clearly be levied on a flat rate basis, much like insurance premiums, since capacity costs are incurred independently of usage levels. Default capacity charges may not be mandatory, in which case facility bypassers may have to build their own back-up capacity. In either case, the cost of facility bypass is increased and the social costs associated with widespread economically inefficient bypass are reduced. The structure underlying default capacity charges is not without regulatory precedent. Similar concepts are currently being explored in both the natural gas and electric industry.

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Competition in the Local Loop: Pricing Carrier Access

by

Steve G. Parsons*

INTRODUCTION

Carrier access represents a major telecommunications market with national revenues pushing towards twenty billion dollars annually. Because of new and changing technology, new providers of service and changing regulatory factors, this market has become increasingly competitive over time. The pricing of this increasingly competitive service has received substantial attention in virtually all jurisdictions since carrier access charges were introduced.

The purpose of this paper is to describe and evaluate alternate carrier access pricing approaches and to present the results of one approach which has been used in several jurisdictions.

PRICING APPROACHES

Two basic pricing approaches can be used for carrier access: one which relies on calculations of the "full cost" of the service and the second which considers market factors in addition to the economic costs of service.

The "full cost" approach seeks to identify the "proper" method of allocating the costs of the local network between local access and carrier access. Such an approach is inappropriate for two primary reasons. First, local access is a separate and identifiable

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service. The demand to have the option to use the local network (local access) causes the vast majority of the costs which are categorized as the costs of local access in typical cost calculations. Second, even if such costs were joint between local and carrier access, cost allocations are necessarily arbitrary and have no theoretical content.

In addition, cost-based discussions of carrier access pricing cloud and/or ignore market factors which are critical to the pricing decision. Even the "costing" terminology is misleading; the "cost" of carrier access is broken into an NTS (non-traffic sensitive) and TS (traffic sensitive) component. The TS component often overstates the marginal cost of providing the service itself and the NTS component has no economic meaning. The terminology provides the misleading impression that two services are available while only one service exists. As one would expect, such a "full cost" approach leads to poor pricing decisions.

The appropriate carrier access pricing approach considers not only the economic costs of providing the carrier access service but other market factors as well. Alternative methods of supplying carrier access, the elasticity of demand for the final services for which carrier access is used as a factor input, and other market factors are relevant for the analysis.

One taxonomy of "market-based" standards identifies three possible market based approaches: contribution maximization, Ramsey pricing, and a multiple criteria approach.

In economic theory, and in many industries, contribution maximization is the stated objective for firm behavior. In addition,

pricing carrier access to generate maximum contribution provides the regulatory authority with the opportunity to reduce (or to limit increases over time) the price of local access, which is often a social or political goal. However, multi-service local exchange companies are not required to price their other services at contribution maximizing prices and, therefore, contribution maximization for carrier access alone would seem to violate both efficiency and equity considerations.

Ramsey pricing is a market-based approach which provides one definition of "efficient" service prices subject to the constraint that the firm faces joint and common costs in production. If independent demands for services exist, this approach requires that the prices for the local exchange company's services exceed marginal cost to a degree which is inverse to the own-price elasticity of demand for each service. This leads to a minimum percentage quantity deviation from the quantities demanded at the first-best prices (equal to marginal costs).

The Ramsey pricing approach is theoretically and intellectually appealing. However, there appear to be no empirical calculations of Ramsey prices in telecommunications which are in the public domain. The absence of public domain results in this area is somewhat disappointing and one can only hope that additional research will be performed and that public policy makers will consider such research as it becomes available.

The final "market-based" approach which is considered in this paper is one which utilizes multiple criteria. Three criteria

are considered: average customer bills, contribution maximization from carrier access and risk to the local exchange company. These criteria correspond to the major regulatory/political concerns in the industry and as such this approach represents a focus on market factors while recognizing regulatory constraints and objectives.

The remainder of this paper describes the modeling approach in more detail and presents the results of applying this approach in several jurisdictions.

MODEL APPROACH

An economic simulation model was used in several jurisdictions to determine a market-based price for switched carrier access using the three criteria described above. The model allows for the explicit consideration of price effects through own- and cross-price elasticities as well as dynamic effects (non-price induced or disequilibrium effect levels of bypass of the local exchange companies network). Three categories of firms were considered in the model: local exchange companies, interexchange carriers and private system providers. Both the local exchange companies and the interexchange carriers were constrained to earn their allowed rate of return through equal percentage changes in the prices for interexchange carrier services and changes in the price of residence local access for the local exchange company. Placing the local exchange company repricing burden on the residence local access price drives the results to represent a "worst possible case result" for the politically sensitive residence local access service.

The required inputs for the model include the price,

quantity and marginal cost for each of the services defined. Also required is a matrix of own- and cross-price demand elasticities. In addition, dynamic or disequilibrium shocks are imposed on the model in the form of bypass quantity shifting. Bypass activity was modeled to include losses in contribution from switched access, gains in contribution from special access, and other quantity shifting effects.

EMPIRICAL RESULTS

The major empirical results include the market price for switched access, average customer bills and levels of utilization of the network. Because this work has been performed in several jurisdictions, the results are presented as ranges; each range describes the tendency for results although, in some instances, particular results for a specific jurisdiction might fall outside the range.

By the criteria established above, the market-based switched access price is between $.04 and $.05 per access minute. Non-traffic sensitive and traffic sensitive components of this charge are meaningless for the reasons discussed earlier. This represents a single average price per average access minute but WATS/MTS or originating/terminating differentials were calculated in a limited number of jurisdictions. In those instances where the carrier access service was disaggregated, the market-based WATS/MTS differential was determined to be around $.015, while the closed end/open end market-based differential was estimated to be in the range of $.01 to $.015.

The average bill calculations were made as a comparison between continued carrier access pricing at the level existing at the time of the study and pricing at the market-based level. The average

residence customers bills were calculated using the base period or historical quantities in order to represent an approximation to a consumer surplus calculation. Market-based pricing, in contrast to continued pricing at existing levels for carrier access, yields an increase in average residence local bills of between $.50 and $2.00 while residence toll bills fell between $1.00 and $3.00. The net result was a reduction of between $1.00 and $2.00 in the average total residence bill.

The effects of market-based pricing on network utilization are substantial. When comparing the results of market-based pricing to continued pricing at levels existing at the time of the studies the increase in switched access utilization is between 15% and 30% while increases in toll and toll-like usage is 10% to 25%. Unlike the average bill results, these results do include stimulation and repression effects.

CONCLUSION

Unfortunately, much of the carrier access pricing debate has centered on artificial cost allocations which are confusing, misleading, and necessarily arbitrary. In contrast, marginal costs and market factors are critical to the determination of an appropriate price for carrier access. The possible market-based approaches to carrier access pricing include contribution maximization, Ramsey pricing, and multiple criteria approaches. While Ramsey pricing is appealing, no current public domain estimates exist. A multiple criteria approach allows explicit consideration of political/regulatory objectives such as average customer bills, service contribution

and risk to the local exchange company. An economic simulation model was used to identify a market-based price for switched carrier access in several jurisdictions in the range of $.04 to $.05 per access minute. Such a price leads to lower total bills for the average customer and greater utilization of the network in comparison to continued prices at levels existing at the time of the studies.

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THE ECONOMICS OF BYPASS

IN A SIMPLE MODEL OF THE TELEPHONE NETWORK*

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May 1987
Revised September 1987

Abstract

The phenomenon of "bypass" is studied in a stylized model of the telephone system. We explore the correspondence between the efficient network configuration and the equilibrium of an entry game played by a local exchange carrier (LEC) and potential bypassers.

A LEC provides local service and carrier access using a hub-and-spoke network in which each connection exhibits cost subadditivity. Cost efficiency may require complete or partial bypass, or none at all. The ability of the market to sustain the efficient network is examined in the special cases of fixed demands and unit-elastic demands with constant marginal cost. We find that there may be no rates that impede cost-raising bypass. This holds even if the LEC employs Ramsey prices which by design discriminate against carrier access on the shared portion of the local network. Unchecked, however, the LEC could exploit its franchise monopoly over local service to successfully deter efficient bypass.

Sunk investment may exacerbate both types of market failure. The cost advantage of preemptive investment allows the LEC to further discourage efficient bypass. But if investment in bypass facilities is sunk when rates were artificially high, subsequent resort to cost-based pricing may fail to drive out inefficient providers. Finally, we explore the potential gains of fine-tuning bypass incentives by coordinating the LEC's tariff with toll rates.

* I want to thank George Bittlingmayer for his written comments on an earlier draft. This paper was presented at the Sixth Annual Conference of the Rutgers University Advanced Workshop in Public Utility Economics and Regulation, Bolton Landing, NY, May 27-29, 1987, and at the Fifteenth Annual Telecommunications Policy Research Conference, Airlie, VA, September 27-30, 1987.

IR013181

1. INTRODUCTION

As telecommunications enters an era of deregulation and technological change the phenomenon of "bypass" has emerged as a key determinant of the industry's new structure. Bypass occurs when facilities, erected alongside a public network, provide close substitutes for a selected set of its services. For example, bypass of a local telephone exchange occurs when end-users connect directly to an interexchange carrier for the purpose of making long-distance calls. It occurs in broadcasting when a viewer intercepts cable transmissions with a satellite dish. Widespread growth of bypass threatens to undermine the viability of the existing systems for providing network services. To gain an understanding of the forces that cause bypass and to assess its desirability, we study the incidence of bypass in the setting of a telephone network.

Reports are mixed over the extent of current bypass activity in the U. S. market.[1] Certainly some of this bypass has been artificially induced by rates that bear little relation to the true costs of local and toll offerings. The standard practice of flat-rate local service coupled with toll rates inflated with excessive, usage-sensitive access fees gives users -- especially large ones -- reason to seek out alternatives. New developments in transmission continue to drive down the cost of bypass without significant degradation of quality, and at the same time that subscriber demands for sophisticated data and video services outstrips the capabilities of the existing network.

While no doubt important, these factors tell only part of the bypass story. There is reason to believe that conditions prevail in telecommunications networks that may naturally invite bypass. Networks of any sort economize on investment outlays by sharing facilities

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[1] There have been dozens of surveys of bypass activity in the telephone industry, many of which are cited in F.C.C. (1985) Appendix 6 and Huber (1987), Appendix E.

among numerous subscribers and across different services. These savings do not come without a tradeoff, however. The transmission and switching costs of long, circuitous routes become significant for sparse network architectures. The additional costs must inevitably turn up in rates for service and customer classes, making these markets prime targets for competitors to pass on the benefits of direct routing. The ability of an integrated network to meet this competition is limited because to do so it must draw on earnings from other parts of its network. Consequently, it is not obvious there are any rates that eliminate all opportunities for profitable bypass -- even when it may raise the cost of service.

That is not to say the local exchange carrier always operates from a position of weakness or that bypass is always wasteful. Some amount of bypass may actually be a necessary part of an efficient network configuration. Certainly, as diseconomies arise on congested switches and circuits there are savings from re-directing traffic along alternative routes.[2] Given franchise protection and sufficient pricing flexibility, however, an integrated network has the ability to deter bypass that otherwise would realize these economies. Deterrence becomes even easier when a large portion of the network plant and equipment of the incumbent provider is sunk, giving it an effective cost advantage over a bypasser.

These ideas are developed using a stylized model of the telephone network. We begin by exploring the relationship between scale economies and the efficient network configuration.[3] Next, criteria of sustainability and efficiency are proposed to evaluate the equilibrium of an entry game played by the local exchange carrier (LEC) and a potential bypasser.

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[2] This is clear when alternative routes accept traffic overflow during peak periods, or during service interruptions. See Sharkey (1982) pp. 193-197.

[3] Bittlingmayer (1985) recently conducted an exercise of this sort using a model of an airline network. In contrast to our results, he finds uninnovative entry is never a threat to the efficient configuration. Our model better describes industries in which there is a physical network (e.g., railroads, pipelines) since, unlike Bittlingmayer, each connection incurs a fixed cost.

The correspondence between the two criteria is studied in the special cases of fixed demands and unit-elastic demands with constant marginal cost. By and large, our suspicions about the sustainability of the efficient network are confirmed:

- Cost subadditivity of individual connections does *not* imply bypass is inefficient: the least-cost network may require partial or complete bypass even though service between any two points constitutes a natural monopoly.
- The LEC may be vulnerable to cost-raising bypass, even when it enjoys a monopoly over local service, and even when it obeys Ramsey optimal pricing rule. Unchecked, however, the LEC could exploit its franchise monopoly to successfully deter *efficient* bypass.
- In the case of fixed demands, both kinds of "market failure" can be avoided if a strong cross subsidization condition holds.
- When demands are unit-elastic, a narrow range of circumstances will usually (but not always) exist in which Ramsey prices generate the correct level of bypass. Incidentally, such prices call for discrimination against toll calls for identical service on the shared portion of the local network.
- Sunk costs alter the incentives for bypass. The LEC can further cut access rates to discourage additional bypass when its fixed costs are sunk. A return to cost-based pricing, however, may fail to drive out inefficient bypass if investment in these facilities was sunk earlier when rates were more attractive.
- There may be gains to coordinating the pricing of the LEC and long distance carriers, a remedy that runs counter to the recent trend toward divestiture of local and toll services and price competition in the interexchange market.

2. A STYLIZED MODEL OF THE TELEPHONE NETWORK

Imagine a phone system composed of several local exchanges linked together by long-distance transmission facilities. Each local exchange (LE) has a hub-and-spoke architecture with n subscribers. Local customers are clustered around a single "central office" as pictured in Figure 1. Subscribers demand two types of service: local calls to another person in the same LE and long distance calls to a distant exchange. A local call uses two "local loops" connected through the central office. Besides an interexchange circuit, a long distance call requires a connection from the customer to the interexchange carrier (IXC). We will refer to this service as "carrier access." The LEC provides access service through a local loop and an interoffice trunk that connects to the IXC's point of presence (POP) in the local area. It is often called "switched access."

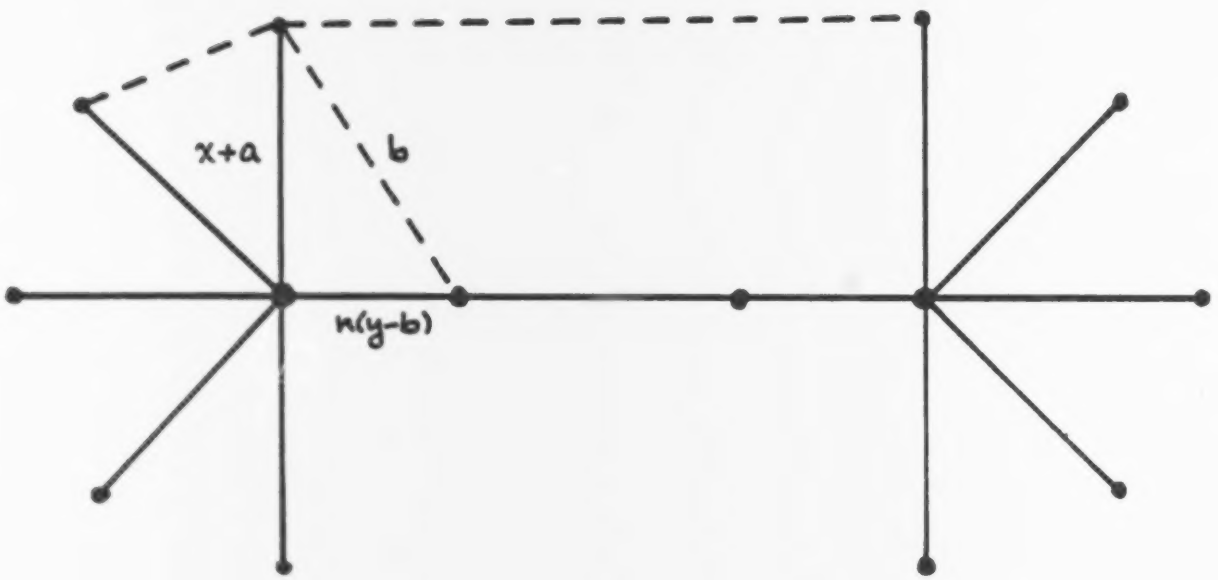

Figure 1: Schematic of the Telephone Network

Three possible types of bypass are depicted in Figure 1: (1) within a local exchange; (2) between local exchanges; and (3) access to an interexchange carrier. Intra-exchange bypass between end-users can be accomplished through a local area network, a two-way coaxial cable system, or a cellular radio network, to name a few. Microwave and satellite facilities are used to directly connect subscribers in different LEs. Short-haul microwave systems are the most popular means of carrier access but optical fiber has been gaining ground as its cost falls. We are concerned with the third type of bypass.[4]

Denote the level of local traffic per subscriber by x and long distance service by y.[5] If the amount of switched access is a, then total traffic on each local loop amounts to $x + a$.. Let the level of bypass be b. Then since each minute of a long-distance call requires a minute of access, the sum of the two types of access equals toll usage: $y = a + b$. In fact, access bypass usually occurs only at the originating end of a long distance call; this feature is lost because traffic is not distinguished by whether it is incoming or outgoing.

2.1 COST CONDITIONS

Each local connection requires a fixed cost of F and variable cost of $C(z)$ where $C(0) = 0$ and $C'(z) > 0$, z being the amount of traffic on the line. Variable cost includes all traffic sensitive expenditures on transmission, switching, signalling, and metering. Many technologies, however, have negligible operating costs. In that case, variable costs amount to

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[4] Access bypass has been further divided into service and facility types. Service bypass occurs when the LEC offers a dedicated access line, or "special access", at reduced rates in competition with its own switched access. We focus on facility bypass because special access is just another offering in the LE's product line.

[5] In terms of traffic flows, it is as if every subscriber places $\frac{1}{2}x/(n - 1)$ calls to each of the other $n - 1$ local subscribers, and $\frac{1}{2}y/mn$ calls to each of n subscribers on m other LEs.

the cost of installing any capacity that varies with the level of traffic.

We make the crucial assumption that the total cost of service is subadditive:

$$C(z' + z'') + F < [C(z') + F] + [C(z'') + F] \quad (1)$$

Subscribers are linked by a hub-and-spoke network, and because every link is a natural monopoly, an exact duplicate of this configuration would only raise the cost of service. Of course, other arrangements are possible. None have fewer connections, however, so if the fixed cost is large enough, then the hub-and-spoke configuration at least minimizes connection costs. Furthermore, as a consequence of subadditivity, a single trunk from the central office to the POP is cheaper than multiple connections. The total cost of the LE is just the sum of the costs of the n local loops and the interoffice trunk:

$$n[C(x + y) + F] + C(ny) + F \quad (2)$$

We have ignored expenses associated with construction and use of the central office. It would also be more realistic to have the fixed cost of the interoffice trunk differ from that for the local loop. Fortunately, the qualitative implications of the model do not change if we generalize the cost conditions along these lines.

Like the LE, bypass facilities connect customers to the IXC, but without the added cost of an interoffice trunk. For this reason, bypass may be cost effective even though it nearly doubles the number of lines. Complete bypass ($b = y$) is more (less) expensive than no bypass ($b = 0$) according to whether:

$$n[C(x) + F] + n[C(y) + F] > (<)\ n[C(x + y) + F] + C(ny) + F \quad (3)$$

or equivalently,

$$[C(x) + F] + [C(y) + F] - [C(x + y) + F] > (<) [C(ny) + F]/n \qquad (4)$$

The left side of (4) is positive by subadditivity and equals the savings of a shared system over two separate sets of access lines. The right side amounts to an equal apportionment of the cost of the interoffice trunk. Again using subadditivity, it is bounded above by $C(y) + F/n$ which converges down to $C(y)$, the total variable cost per line. Thus, the greater the number of subscribers the *less* likely bypass will be cheaper.

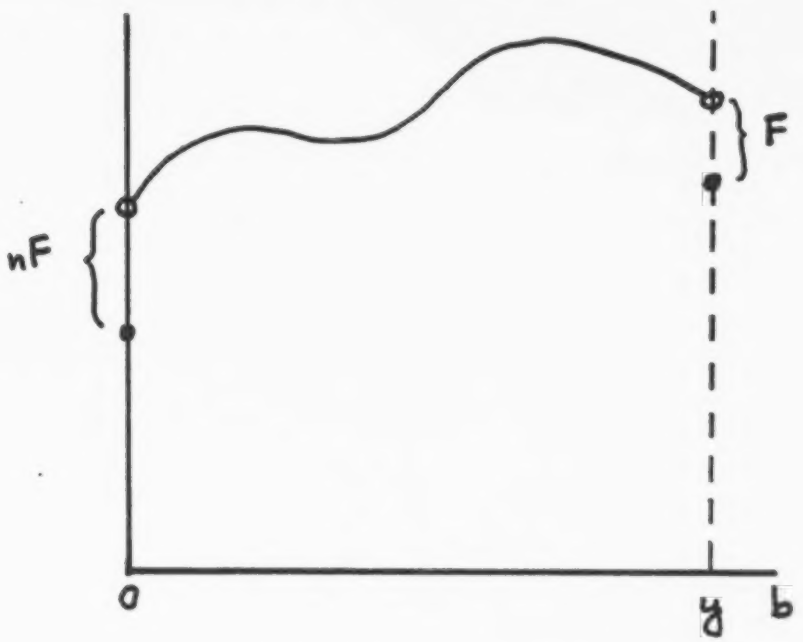

Figure 2: Cost for Different Levels of Bypass

The least-cost network may require only partial bypass.[6] For a given level of local and long distance traffic the cost of the network with some bypass ($0 < b < y$) is given by:

$$n[C(x + y - b) + F] + C(n(y - b)) + F + n[C(b) + F] \qquad (5)$$

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[6] This can be demonstrated for certain values of n and F when variable cost is quadratic $C(z) = z^2$, in which case subadditivity holds provided $z \leq \sqrt{2F}$.

A necessary condition for an interior minimum is that variable cost cannot be everywhere concave, or in other words, there cannot be economies of scale at all traffic levels.

Figure 2 shows how total cost varies with the amount of bypass. Cost jumps up by nF when the bypass lines are installed, and jumps down by F when all access is routed through these facilities making the interoffice trunk useless. Were this trunk not needed, bypass would always be redundant. On the other hand, additional costs of handling both types of traffic on the same network invariably arise, and these costs would also serve to induce bypass.

2.2 PRICING AND DEMAND

For the sake of generality, connection to and usage of the network are priced separately. Customers face a two-part tariff for each service: let t_x, t_a, t_b be the lump-sum connection charges, and p_x, p_a, p_b be the unit prices for local exchange service, switched access, and bypass, respectively. At times, it will be necessary as well to refer to the long distance tariff: p_y, t_y. Providers of interexchange service may negotiate payments to the LECs for access to their networks, but without loss of generality, it is assumed the fees are passed on to end-users dollar-for-dollar.

As an example of this pricing scheme, consider the typical tariff that offers local service at a flat rate and charges for access based on usage and connection, or in our notation, $p_x = 0$ and $t_x > 0$. Until recently the Separations Procedure stipulated that, in addition to those expenses directly attributable to access service (here the interoffice trunk), a part of the costs of facilities shared with local service be recovered through the access portion of toll rates according to "relative use." In the absence of bypass, this takes the form:

$$p_a y = [C(ny) + F]/n + s\,[y/(x + y)]\,[C(x + y) + F] \qquad (6)$$

where $y/(x + y)$ is "subscriber line usage" and s, a positive number, is the so-called "subscriber plant factor." The SPF, which is itself based on the SLU, has been as high as 3.3.[7] With the advent of the Federal Communications Commission's Access Charge Plan, traffic-insensitive cost has been recovered in part by flat access charges, $t_a > 0$.[8]

Customers have identical preferences which are represented by the utility function:

$$U(x,y,m) = U_x(x) + U_y(y) + m \tag{7}$$

where m is money. It is convenient to assume away any income effects, and to treat demand for local and toll service as independent. In choosing carrier access, subscribers face a discrete-continuous choice problem: maximize utility under each tariff, and select the mode of access that yields the higher utility. The nontrivial cases occur when $p_a > p_b$ and $t_a < t_b$, or when $p_a < p_b$ and $t_a > t_b$. Either way, subscribers face a kinked budget set as in Figure 3. For each type of access $i = a, b$ the consumer solves the problem:

$$\text{Maximize } U_x(x) + U_y(y) - t_x - t_i - t_y - p_x x - (p_i + p_y)y \tag{8}$$

Below, p_y, t_y and m are suppressed as they will be held constant for the most part, often writing associated demands as $x_i = X(p_x, p_i, t_x + t_i)$ and $y_i = Y(p_x, p_i, t_x + t_i)$. Let $V_i = V(p_x, p_i, t_x + t_i)$ be the subscriber's indirect utility using different forms of access. Bypass is chosen over switched access whenever $V_b > V_a$. Incidentally, because there are no income effects, the ordering of the two types of access is independent of subscribers' initial income as well as the connection charges. In general, however,

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7 See F.C.C. (1985), Appendix 7, p. 5.

8 Strictly speaking, the FCC's access charge differs from our t_a because it must be paid as long as some local service is used, even if no toll calls are made.

customers might switch back and forth between the two options as income (or connection charges) vary.

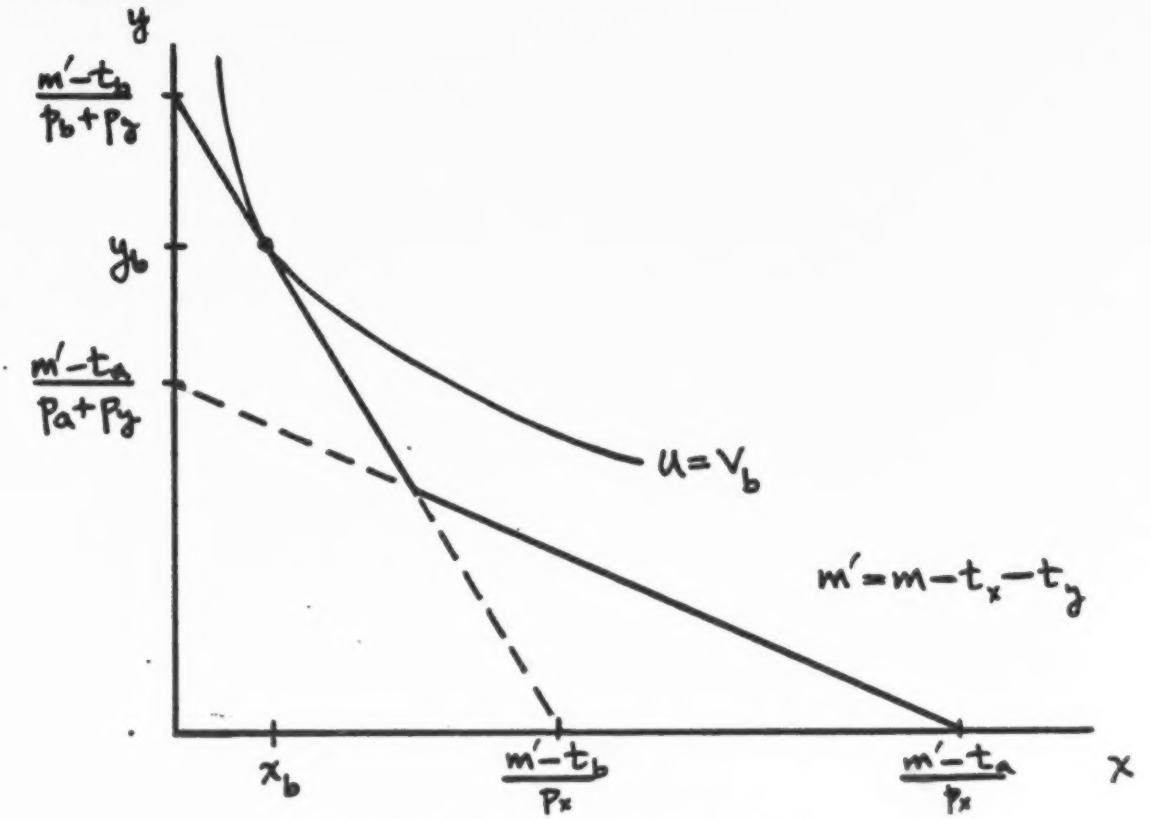

Figure 3: The Subscriber's Choice Problem

This demand specification has several limitations, the most restrictive being that subscribers are identical in every way.[9] They have the same tastes and income, and they are equally costly to serve as though they are distributed equidistant from the central office over a uniform landscape. Without some variation across subscribers, the model is silent on distributional issues (e.g., the problem of "dropoff"). In defense of this specification, it

[9] There are several others: customers apparently do not perceive any qualitative difference between the two types of access while, in fact, bypass is often motivated by the inability of the LE to provide adequate data and video transmissions. On the other hand, bypass facilities have a poor reputation for reliability, often leading customers to employ them as a "second source" alongside switched access. Also, users show no preference for incoming and outgoing traffic, nor do their preferences depend on who else is on the network as might be expected.

should be observed that wide variations across subscribers (and costs of service) only serve to enlarge the opportunities for inefficient bypass since then the entrant need attract only a portion of the population.

3. SUSTAINABILITY AND EFFICIENCY OF BYPASS

The LEC and a potential bypasser engage in an entry game in the market for access service. The two firms move sequentially. Play begins when the LEC sets rates for local service and switched access. If there is a profit opportunity, the bypasser announces its tariff and invests in transmission facilities. The LEC's tariff is said to be sustainable if it breaks even and if there are no bypass rates that will attract customers and also cover the cost of investment. More formally,

Definition: The tariff (p_x, p_a, t_x, t_a) is *sustainable against bypass* if:

i) the LEC is profitable:

$$n(p_x x_a + p_a y_a + t_x + t_a) - n[C(x_a + y_a) + F] - C(ny_a) - F \geq 0 \quad (9)$$

ii) bypass is not viable: there is no (p_b, t_b) such that:

a) $V_b > V_a$ (10)

b) $p_b y_b + t_b - C(y_b) - F \geq 0$ (11)

This notion closely parallels the one found in the literature on sustainability of natural monopoly (Baumol, et. al. (1982)). As in that literature, there are no entry or exit barriers facing the bypasser and the LEC is precluded from adjusting its tariff in response to entry. Also, the bypasser is a "full-supplier entrant" since it is required to garner all of the LEC's access business, and to satisfy all realized demand. Our formulation differs in a couple of ways, however. First of all, firms sell their services using two-part tariffs, and not uniform

prices. To be precise, each service consists of two separate products – connection and transmission – which are needed in that order. So while individually priced, they are sold as a bundled product. Second, the LEC faces a threat of entry only in the market for carrier access: its franchise over local service remains secure.

The efficiency of the outcome of the entry game is measured by the cost of providing the resulting levels of service. To avoid comparing the market equilibrium to an alternative that fails a profitability test, efficiency is checked at the service levels (x_b, y_b) if bypass is viable, and at (x_a, y_a) when it is deterred:

Definition: Bypass is *cost efficient* when:

$$n[C(x_i + y_i) + F] + C(ny_i) + F > n[C(x_i) + F] + n[C(y_i) + F] \qquad (12)$$

where $i = b$ if bypass occurs and $i = a$ otherwise.

Our objective is to delineate the extent of the overlap of these two criteria in different institutional settings. The two definitions partition tariff structures into a number of distinct possibilities. Four possibilities remain according to whether or not bypass is viable, and whether or not it is cost efficient. We will be especially interested in the two instances of "market failure" that arise when bypass is viable but not efficient, and vice versa.

A complete analysis would require an examination of the full range of possibilities for the six rates for connection and usage. This task is made easier by solving for the equilibrium tariff set by the bypasser. From (10) and (11), the most potent entry threat a bypasser can make is to offer subscribers the highest level of utility consistent with breaking even. The solution, first suggested by Coase, prices usage at marginal cost and sets the fixed fee to ensure solvency:

$$p_b^* = C'(y_b^*) \tag{13}$$

$$t_b^* = C'(y_b^*)y_b^* - C(y_b^*) - F \tag{14}$$

where $y_b^* = Y(p_x, p_b^*, t_x + t_b^*)$. Thus, bypass is feasible if and only if it attracts customers using the Coasian two-part tariff. This rule is not necessarily an equilibrium strategy since an entrant could do better than break even. However, if there are many potential bypassers vying for the access market, they will bid away any economic profit.

The next step is to determine whether the LEC can deflect this attack on its access market. Naturally, its ability to do so hinges on the degree of pricing flexibility it enjoys. Without any restrictions on rates, the LEC's problem amounts to choosing unit prices and fixed fees to eliminate any opportunity for profitable bypass, provided that it is able to break even:

$$p_x x + p_a y + t_x + t_a \geq C(x + y) + F + [C(ny) + F]/n \equiv \bar{c} \tag{15}$$

where $\bar{c}$ is short-hand for cost per customer. In so doing, it shifts the full burden of cost recovery to local service, at least up to the point that subscribers opt to do without service altogether.

Alternatively, the LEC may set prices so as to maximize some measure of social welfare subject only to financial viability, e.g., Ramsey pricing. Provided demands are independent the Ramsey rule calls for a mark-up over marginal cost which varies inversely with price elasticities:

$$[p_x - C'(x + y)] / p_x = \rho/\epsilon_x \tag{16}$$

$$[p_a - C'(x + y) - C'(ny)] / p_a = \rho/\epsilon_a \tag{17}$$

where ϵ_x and ϵ_a are the price elasticities of demand for local and access service, and where ρ is the "Ramsey number" that ensures the firm breaks even. Since demand for access equals demand for long distance service, the two elasticities are related according to $\epsilon_a = \epsilon_y(p_a + p_y)/p_a$.

To complete the solution, the fixed fees must also obey a rule in which they vary inversely with the elasticity of demand for connection to the network. Up to this point, however, the number of subscribers has been fixed. Rather than model connection demand at this stage, we consider "partial Ramsey pricing" in which the sum of the fixed fees equals the marginal (and average) connection cost:[10]

$$t_x + t_a = F \tag{18}$$

It is important to remember that these prices solve the welfare problem when there is no bypass.

Marginal-cost pricing of all services is a special case of partial Ramsey prices when $\rho = 0$. Not surprisingly, as a result of scale economies, full marginal-cost pricing creates a budget balancing problem for the LEC. As it turns out, nonincreasing average variable cost is sufficient (but not necessary) for marginal-cost pricing to be unprofitable.[11] Cost may be subadditive even though average cost is not everywhere declining, in which case the LEC will make a profit.

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10 (18) gives the correct Ramsey prices when demand for connection is infinitely elastic.

11 Average cost declines if and only if it exceeds marginal cost so $n(x + y)C'(x + y) < nC(x + y)$ and $nyC'(ny) < C(ny)$. Summing, we have $n[p_x^* x + p_a^* y + t_x^* + t_a^*] < n[C(x + y) + F] + C(ny) + F$, where we have used $t_x^* + t_a^* = F$. Thus, the LEC is unprofitable.

4. FIXED DEMANDS

In order to isolate the role of cost conditions, we first treat the case of fixed demands, a standard approach in the literature on network equilibrium. It can be derived from first principles by taking subscriber utility to be:

$$U(x, y, m) = r_x \min\{x, \bar{x}\} + r_y \min\{y, \bar{y}\} + m \tag{19}$$

where r_x, r_y are reservation prices for local and long-distance service. Demands generated by the consumer problem have a rectangular shape: $X(p_x) = \bar{x}$ if $p_x \leq r_x - t_x/\bar{x}$ and $Y(p_i + p_y) = \bar{y}$ when $p_i + p_y \leq r_y - (t_i + t_y)/\bar{y}$. (Note that demand for local service is independent of toll rates.) Indirect utility is linear in prices and quantities: $V_i = - p_x\bar{x} - (p_i + p_y)\bar{y} - t_x - t_i - t_y$ and as a result:

$$V_a \gtrless V_b \longleftrightarrow p_a\bar{y} + t_a \lesseqgtr p_b\bar{y} + t_b \tag{20}$$

so whichever mode of access is cheaper will be the preferred alternative. In addition to the reservation prices, the LEC's rates must break even. Using (15), we get:

$$\bar{c} - r_x\bar{x} \leq \bar{c} - [p_x\bar{x} + t_x] \leq p_a\bar{y} + t_a \leq (r_y - p_y)\bar{y} - t_y \tag{21}$$

establishing a lower bound on revenue from access service.

4.1 ENTRY EQUILIBRIUM

We begin by constructing the bypasser's entry tariff described above. In the case of fixed demands the exact amounts for p_b° and t_b° are immaterial since, from (20), all that matters to subscribers is the size of the "access bill." If revenue just covers cost, bypass is viable when:

$$p_a\bar{y} + t_a > C(\bar{y}) + F \tag{22}$$

The right side of (22) is the cost per subscriber of a stand-alone access system.

When demands are fixed the efficiency condition (12) no longer depends on which tariff prevails. Recognizing that the left side of (12) equals revenue per customer when the LEC breaks even, it can be written as:

$$p_a\bar{y} + t_a > C(\bar{x}) + C(\bar{y}) + 2F - [p_x\bar{x} + t_x] \tag{23}$$

Bypass is viable if and only if it is cost efficient provided conditions (22) and (23) coincide. Equating the right sides of the two inequalities yields the necessary condition:

$$p_x\bar{x} + t_x = C(\bar{x}) + F \tag{24}$$

which is to say local service revenue equals its *stand-alone* cost. (Unrestricted entry into the market for local service would limit revenue to this amount.) Substituting the zero-profit condition, (24) can also be expressed as:

$$p_a\bar{y} + t_a = \bar{c} - [C(\bar{x}) + F] \tag{25}$$

which equates the LEC's access revenue with the *incremental* cost of that service. Conditions (24) and (25) are familiar requirements for absence of a cross subsidy between two services. They continue to hold when pricing is nonuniform as a consequence of the fixed demand assumption.

The linearity of surplus and profit produces an unusual solution to the welfare problem: there is not one but rather a continuum of optimal prices. For any given total connection charge $t_x + t_a$ optimal prices satisfy:

$$p_x\bar{x} + p_a\bar{y} = \bar{c} - F \tag{26}$$

The range of admissible prices is inscribed in Figure 4 for different allocations of connection costs. Left to pursue its own interests the LEC will collect all connection charges from local service and none from switched access: $t_x = F$, $t_a = 0$, and $p_x = r_x - F/\tilde{y}$, in which case (26) dictates $p_a = (\tilde{c} - r_x\tilde{x})/\tilde{y}$. Bypass occurs in spite of this as long as:

$$(\tilde{c} - r_x\tilde{x})/\tilde{y} > [C(\tilde{y}) + F]/\tilde{y} \tag{27}$$

or equivalently,

$$\tilde{c} > r_x\tilde{x} + C(\tilde{y}) + F \tag{28}$$

Now rewriting (12) we find that bypass is cost efficient when:

$$\tilde{c} > C(\tilde{x}) + C(\tilde{y}) + F \tag{29}$$

Together, (28) and (29) guarantee efficient bypass cannot be deterred; when neither hold, the LEC is able to set tariffs that bar bypassers that would otherwise raise cost.

The less felicitous outcomes occur when one but not the other of these two conditions is satisfied. A sufficient condition ruling out this possibility is given by:

$$r_x\tilde{x} = C(\tilde{x}) + F \tag{30}$$

This condition disallows a type of cross subsidization: revenues from the usage portion of local service (i.e., excluding connection charges) exactly cover its stand-alone cost. This is a very strong restriction on demand and cost conditions owing to the fact that the LEC does not face competition in the market for local service. It is improbable that (30) will be satisfied, so that either efficient bypass will be discouraged or inefficient bypass will occur. Resort to standard prescription that the LEC to cover the stand-alone cost of access with its usage charges will not ensure efficiency.

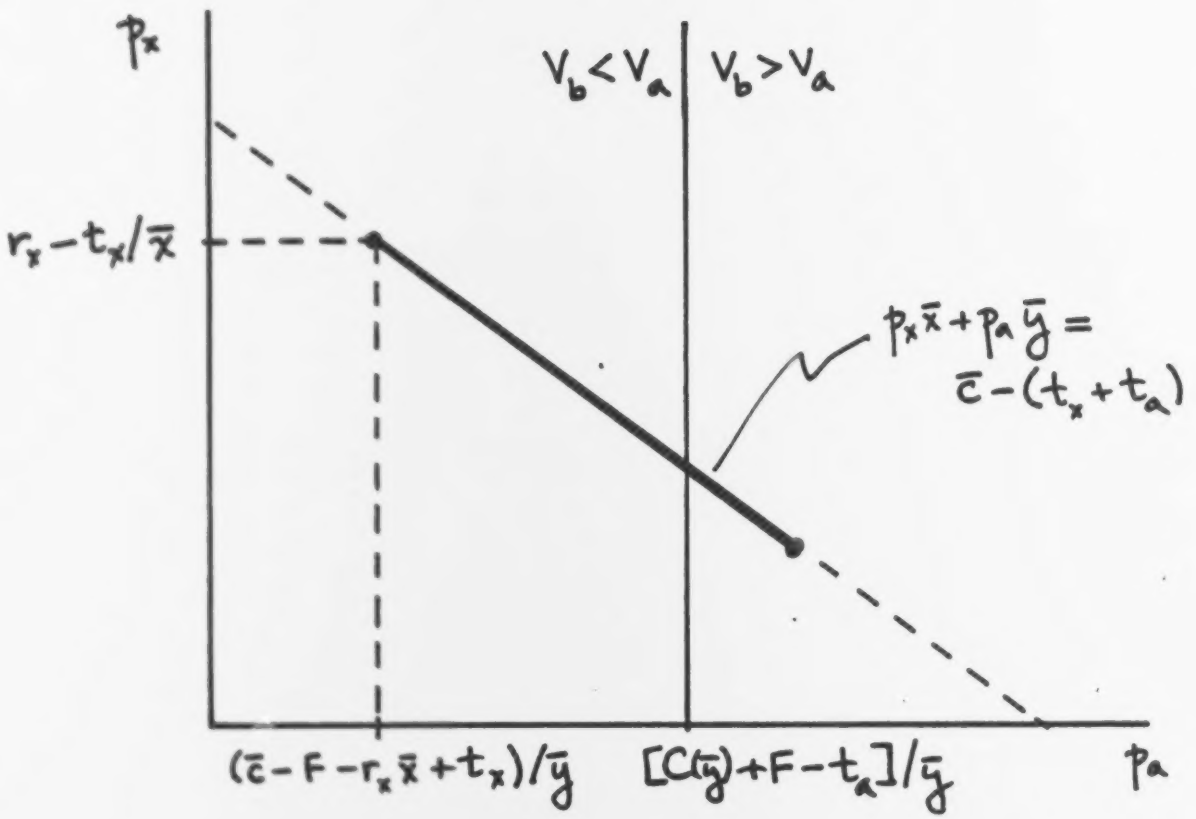

Figure 4: Efficiency and Viability of Bypass with Fixed Demands

Incentives for the two kinds of bypass are affected in opposite ways by changes in cost and demand conditions. For instance, high connection cost (F) will ensure that $r_x\bar{x} < C(\bar{x}) + F$ thereby facilitating bypass. The same is true for a reduction in the reservation price for local service (r_x). Similarly, low F and high r_x makes inefficient bypass more difficult. The impact of demand shifts in the form of increases in $\bar{x}$ is less clear. Increases in $\bar{x}$ will tend to cause $r_x\bar{x} > C(\bar{x}) + F$ provided that $r_x > C'(\bar{x})$; otherwise the reverse holds.

4.2 THE ROLE OF SUNK INVESTMENT

The relevant cost considerations of a firm change once investment in facilities is "sunk" in the sense that the outlay cannot be recovered after it is undertaken. The implications of

sunk investment for bypass activity are straightforward. Suppose the LEC is able to sink the costs of its lines before bypass is legally or technically feasible. Then in principle it can respond to a competitive threat by cutting rates down to avoidable cost which will be much lower than if it had waited until after entry materialized. Intuitively, the LEC can successfully deter bypass that otherwise would have occurred -- whether it was inefficient or not.

This conclusion is easy to verify. Let all fixed cost associated with the local loops and the interoffice trunk be sunk. The break-even constraint on the LEC's tariff is then relaxed:

$$n[p_x x + p_a y + t_x + t_a] \geq nC(x + y) + C(ny) = n\bar{c} - (n + 1)F \qquad (31)$$

This change results in an inward shift of the zero-profit line in Figure 4. Again setting charges for local service at their upper limit, i.e., $p_x + t_x/\bar{x} = r_x$, (31) is:

$$p_a \bar{y} + t_a \geq \bar{c} - F(n + 1)/n - r_x \bar{x} \qquad (32)$$

When none of the cost is sunk, the right side of (32) was just $\bar{c} - r_x \bar{x}$ (see (21)). The LEC has been able to lower its access revenues by $F(n + 1)/n$ thereby making customers less likely to switch to bypass. Whether the increase in deterrence is beneficial depends on the criterion of efficiency. If we adopt the notion of *ex ante* efficiency, then (12) applies and there is no question the likelihood of deterring efficient (inefficient) entry rises (falls).

Earlier it was mentioned that artificially-high charges for switched access pave the way for migration from the local exchange. A potentially a more serious threat to the local exchange stems from the long-term effects of sunk investment. Suppose now that connection costs are irreversible for both providers. If the LEC is the first to invest, its cost advantage may be immaterial if exorbitant charges for switched access are imposed by a regula-

tory authority. Once bypass facilities are in place, they too become sunk costs and the bypasser now enjoys lower avoidable costs. Bypass remains viable as long as:

$$p_a\bar{y} + t_a > C(\bar{y}) \qquad (33)$$

Comparing (33) with (22), and recalling that $t_a = 0$, a bypasser is able to remain solvent at rates for switched access that are lower by an amount F. In terms of Figure 4, there is a leftward expansion of the region of viable bypass.

Irreversibility of investment increases the LEC's ability to deter bypass more than it enhances the bypasser's ability to penetrate the access market: the LEC is able to cut p_a by $F(n + 1)/n\bar{y}$ but the bypasser is able to withstand a reduction of only $F/\bar{y}$. This situation would be conducive to efficiency only when the LEC would otherwise have deterred too much bypass.

It is worth noting that a belated program of "rational" ratemaking may not have intended effects in this situation. While the ability to sink the investment in bypass facilities will partly offsets the LEC's first- mover advantage, the bypasser may continue to thrive. Of course in a full analysis an entrant would take account of post-entry competition in its initial decision to bypass.

5. ELASTIC DEMANDS

The fixity of demand was responsible for the peculiar indeterminacy encountered above. A more realistic specification would have demands for local and long-distance service which are responsive to price. In addition, elastic demands permit us to study the benefits of rate coordination between the LEC and the IXC. A policy of this sort was not an option when demands were fixed since, by construction, there was (virtually) no connection between the two markets.

To keep matters simple, consider the logarithmic utility $U(x,y,m) = \ln(x) + \ln(y) + m$ which yields service demands having unit elasticities:

$$X(p_x) = 1/p_x \tag{34}$$

$$Y(p_i + p_y) = 1/(p_i + p_y) \tag{35}$$

Since we have retained separability, cross-price elasticities are still zero. Because each service generates exactly one unit of revenue, connection charges are constrained by $t_x + t_i + t_y \leq m - 2$ where m is again initial wealth.

Calculations are further simplified by assuming constant marginal cost $C(z) = cz$. The marginal cost of local service is then just c and that for access service is $2c$. As mentioned earlier, this case creates a budget problem for the LEC under marginal-cost pricing.

Once again the viability of bypass depends on its ability to attract customers. The relevant comparison for the utility $V_i = -\ln(p_x) - \ln(p_i + p_y) - t_x - t_i - t_y$ is now a bit more complicated:

$$V_a \gtrless V_b \longleftrightarrow (p_a + p_y)e^{t_a} \lesssim (p_b + p_y)e^{t_b} \tag{36}$$

When evaluated at the bypasser's marginal-cost pricing strategy $p_b^* = c$ and $t_b^* = F$, (36) becomes:

$$(p_a + p_y)e^{t_a} \lesssim (c + p_y)e^{F} \tag{37}$$

On the other hand, constant marginal costs makes the test for cost efficiency (12) especially simple:

$$n[c(x_i + y_i) + F] + cny_i + F > n(cx_i + cy_i + 2F) \tag{38}$$

which, after rearranging, reduces to:

$$y_i > (n - 1)F/nc \tag{39}$$

Hence, bypass is unambiguously cost efficient when toll demand is large enough to exploit its scale economies. If bypass is viable, this condition is written:

$$1/(p_b^* + p_y) > (n - 1)F/nc \tag{40}$$

and when evaluated at marginal cost prices (i.e., $p_b^* = c$), it becomes:

$$c + p_y < nc/(n - 1)F \tag{41}$$

If bypass is not viable, (39) will be checked at the Ramsey prices that are derived below. Unlike the fixed demands case, the price of access usage now becomes a factor through its effect on access demand.

5.1 OPTIMAL PRICING

Given complete pricing freedom, the LEC can easily discourage bypass. Both usage and connection charges for access can be made small by shifting cost recovery from access to local service, as would be expected in the absence of competition in the local service market. More interesting is the question whether optimal prices are able to support the efficient level of entry. In the case of partial Ramsey prices, in addition to setting $t_x + t_a = F$, they satisfy the inverse-elasticity rule:

$$(p_x - c)/p_x = \rho = (p_a - 2c)/(p_a + p_y) \tag{42}$$

together with the breakeven constraint:

$$n\{1 + p_a/(p_a + p_y) - c[1/p_x + 2/(p_a + p_y)]\} - F = 0 \tag{43}$$

Solving, we get $\rho = F/2n$. In order to ensure $\rho \in [0, 1]$ it is necessary to have $2n \geq F$. Inserting $\hat{\beta}$ into (42) yields:

$$\hat{\beta}_x = 2nc/(2n - F) \tag{44}$$

$$\hat{\beta}_a = (4nc + Fp_y)/(2n - F) \tag{45}$$

both of which converge down to their corresponding marginal costs as n grows.

Ramsey pricing discriminates against local traffic in favor of switched access on the shared lines: access service defrays a smaller portion of the common costs of the local loop than does local service, per unit of traffic.[12] To see this, note that revenue from access service *minus* the attributable cost of the interoffice trunk amounts to:

$$n(\hat{\beta}_a - c) - F/\hat{\gamma} = (2nc - 3cF - Fp_y)/(2n - F) \tag{46}$$

which is always *less* than revenue from local service:

$$n\hat{\beta}_x = 2n^2c/(2n - F) \tag{47}$$

This occurs even though access pays a higher mark-up over its marginal cost than local service:

$$\hat{\beta}_a/2c = (2c + \rho p_y)/2c(1 - \rho) > 1/(1 - \rho) = \hat{\beta}_x/c \tag{48}$$

which is to be expected since the elasticity of local service is larger than the elasticity for access service: $\epsilon_x = 1 > p_i/(p_i + p_y) = \epsilon_i$.

When is bypass *viable* under Ramsey prices? Inserting (44) and (45) into (37) we have:

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[12] Bittlingmayer (1985) made a similar observation for shared routes of an airline network.

$$2n(2c + p_y)e^{t_a}/(2n - F) \lesseqgtr (c + p_y)e^{F} \tag{49}$$

To get a handle on this condition, let n grow so that the left side of (49) converges down to $(2c + p_y)e^{t_a}$. In that case only the magnitude of the access connection charge matters:

$$t_a \lesseqgtr F + \ln[(c + p_y)/(2c + p_y)] \tag{50}$$

Hence, if the marginal cost is large relative to the fixed cost, then bypass is inevitable. In particular, when:

$$F + \ln[(c + p_y)/(2c + p_y)] < 0 \tag{51}$$

then there is no nonnegative connection charge that will deter bypass.

When is bypass *cost efficient* under Ramsey pricing? Substituting $y_a = 1/(\hat{p}_a + p_y)$ into the condition (39) and manipulating we have efficiency when bypass is not viable as long as:

$$c + p_y < c[F - 2n(F - 1)]/2F(n - 1) \tag{52}$$

We want to know how this inequality matches with entry incentives given by (49). Comparing the two conditions, if bypass is not viable, we can automatically conclude that it was necessarily inefficient provided:

$$t_a \geq F + \ln\{c(2n - F)[F - 2n(F - 1)]/4nF(n - 1)(2c + p_y)\} \tag{53}$$

The other instance of market failure occurs when bypass is viable despite the fact that it is inefficient. Manipulating (49) and (41) this possibility can be ruled out if:

$$t_a \leq F + \ln[c(2n - F)/2F(n - 1)(2c + p_y)] \tag{54}$$

There is an allocation of the common connection costs which in combination with the Ramsey usage prices eliminates distortions of both sorts when (53) and (54) are satisfied simultaneously. A necessary condition is that the right side of (54) exceed the right side of (53) which, in turn, must be nonnegative.[13] This first inequality reduces to:

$$F \leq 4n/(1 + 2n) \tag{55}$$

Here is a "window" in which Ramsey prices are able to support the correct level of bypass. Of course, there is no guarantee that it exists. And even when it does, blind adherence to popular rules for allocating common cost (e.g., the many fully-distributed-cost formulas) may not bear any relation to the restrictions in (55).

5.2 COORDINATION WITH THE IXC

Demand for carrier access is derived from demand for long-distance calls. Since some of our results turn on the size of access demand, it is logical to explore the pricing of interexchange services as a means to correct misallocations in the access market.

Should the LEC and the IXC merge, they would be able to coordinate their pricing to limit the extent of bypass. For example, in absence of any interexchange competition the integrated firm can implement a "vertical price squeeze" by marking up rates for interexchange service and cutting rates for switched access down to (or below) cost. While a strategy of this sort will serve to curtail the incidence of inefficient bypass, it also raises the risk of deterring efficient bypass.

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[13] It is easy to see that inefficient bypass can be ruled out as long as $nc/(n - 1)F < [2n(2c + p_y)/(2n - F)]\exp(t_a - F)$. Similarly, deterrence of efficient bypass is feasible if $c[F - 2n(F - 1)]/2F(n - 1) > [2n(2c + p_y)/(2n - F)]\exp(t_a - F)$.

So far we have avoided any discussion of payments between the LECs and the IXCs for interconnection. It is possible that such payments can be designed so as to move the level of bypass closer to efficiency. For instance, IXCs' access fees could be based on the amount of interexchange traffic arriving through bypass facilities. Passing along this differential will drive a wedge between toll rates based on the form of access used, thereby promoting or discouraging bypass.

In the presence of interexchange competition, or in an era of divestiture of local and toll, shifting cost away from competitive markets in this way is no longer tenable. As a final alternative, we might consider direct regulation of the level and structure of toll rates regulation. It is easy to show that viability of bypass varies inversely with the toll usage rate p_y. This should be expected since high toll rates reduce access demand and prevent bypass from achieving the necessary scale economies. High toll rates also eliminate the cost advantage of bypass when it occurs. Consequently, one means to curtailing inefficient bypass is to boost toll rates. On the other hand, it can be shown that, under Ramsey-pricing, the cost advantage of the LE falls with toll rates so that deterrence of efficient bypass can be prevented by such a policy.

Fine-tuning bypass incentives through toll regulation requires detailed demand and cost information. Furthermore, whether the level of bypass is adjusted by reduced competition, or controls on prices are implemented, a new allocative distortion in the interexchange market will be introduced. Proper calculation of the net benefits of each approach requires inclusion of the added costs.

6. CONCLUSIONS

We have discovered circumstances in which the efficient provision of local exchange services cannot be unconditionally delegated to the market mechanism. This observation may be true as well to the other varieties of bypass of the telephone network. It may also apply to bypass in other network industries. Bypass has been detected in the natural gas industry when an interstate pipeline delivers directly to industrial customers, and when a cogenerator sells electric power wholesale to another industrial customer rather than back to its local utility.

The prevalence of bypass raises questions about the stability of networks in general. Carlton and Klammer (1985) have investigated the ability of private profit incentives to guide firms to choose the efficient configuration. They isolated the strong dependencies between pricing and investment decisions in remote parts of a network which render these industries especially vulnerable to inefficient entry.

Our findings supply new evidence on the tension between network efficiency and entry incentives. Sparse architectures save on the fixed costs of making connections but raise the variable costs of transmission and switching, leaving open an opportunity for a specialized carrier to enter with a limited network. And market constraints on its ability to transfer earnings from elsewhere in the network may leave a full-service provider powerless to stop it.

At this point, a careful examination is needed of the sustainability of efficient networks in a more general setting. A promising starting point for this line of research would seem to be the study of strategic competition among firms which, in addition to choosing prices, also select the architecture of their network. Needless to say, this is a subject for future research.

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